

DURABILITY OF LOW-EMISSIONS SMALL OFF-ROAD ENGINES

Prepared by

**Chad C. Lela
Jeff J. White**

FINAL REPORT

Prepared for

**CALIFORNIA AIR RESOURCES BOARD
Mobile Sources Operations Division
9528 Telstar Ave.
El Monte, CA 91731**

APRIL 2004

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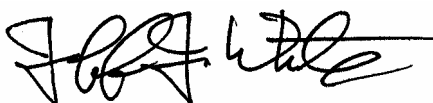
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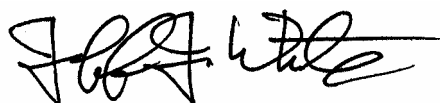
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DEPARTMENT OF ENGINE AND EMISSIONS RESEARCH
ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION

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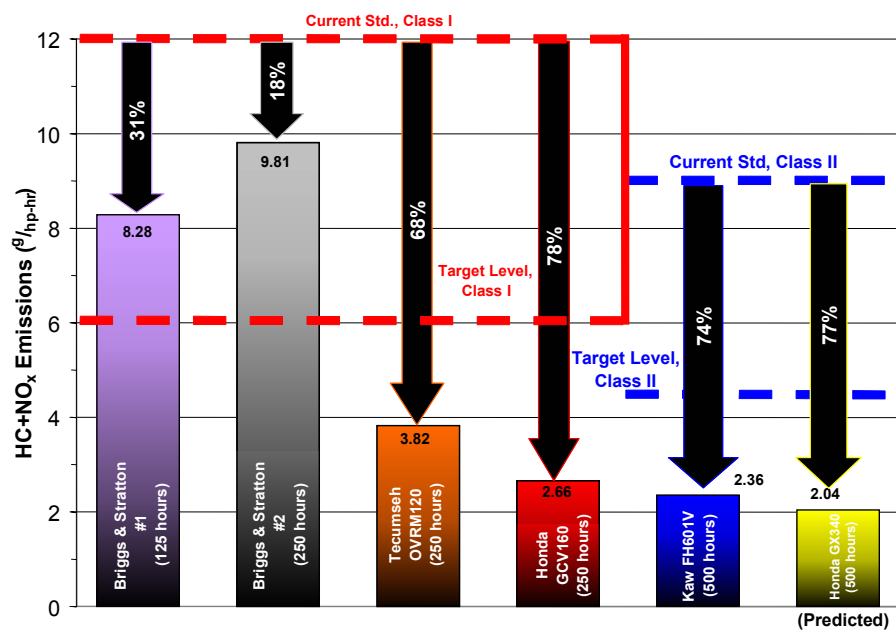
LIST OF ABBREVIATIONS

Appl	Application
BS	Brake-Specific
BSLN	Baseline
CARB	California Air Resources Board
cc	Cubic centimeter
CO	Carbon monoxide
CO ₂	Carbon dioxide
CPSI	Cells per square inch
CVS	Constant Volume Sampling
DER	Department of Emissions Research at Southwest Research Institute
EMA	Engine Manufacturers Association
EGO	Exhaust Gas Oxygen sensor
FID	Flame Ionization Detector
GEN	Generator
G	Grams
HC	Hydrocarbons
Hr	Hour
hp	Horsepower
MECA	Manufacturers of Emission Controls Association
Mfg	Manufacturer
mm	Millimeter
NDIR	Non-Dispersive Infrared
NH ₃	Ammonia
NO _x	Oxides of nitrogen
OPEI	Outdoor Power Equipment Institute
O ₂	Oxygen
PII	California Phase II gasoline
RPM	Revolutions per minute
SAI	Secondary air injection or secondary air induction
SORE	Small Off-Road Engine
TWC	Three-Way Catalyst
WBM	Walk-Behind Mower

EXECUTIVE SUMMARY

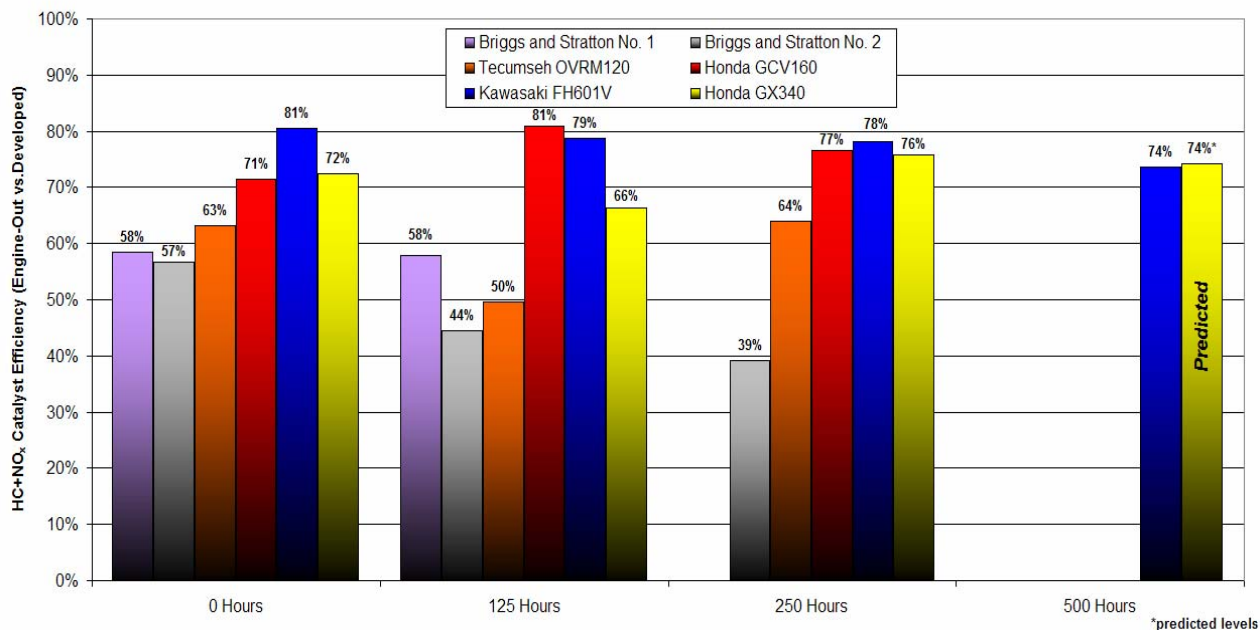
The purpose of this study was to determine whether catalyst technology could be applied to small off-road engines (SOREs) to provide 50% or greater reductions in HC+NO_x emissions throughout the engines' useful lives. Six engines meeting current CARB Tier II standards were selected for development. Engines tested included two Briggs and Stratton Intek engines, a Tecumseh OVRM 120 engine, two Honda engines (GCV 160 and GX340), and a Kawasaki FH601V engine. Four of the engines are used in walk-behind mower (WBM) applications, one is used in a riding mower, and one is used in constant-speed/generator applications. All engines were naturally aspirated, air-cooled, four-stroke, carbureted engines with an overhead valve train. All engines, with the exception of the Kawasaki, were single cylinder.

The goal of the project was to reduce tailpipe-out hydrocarbon (HC) plus oxides of nitrogen (NO_x) emissions to 50% or less of the current California Air Resources Board (CARB) useful life standard of 12 g/hp-hr for Class I engines, or 9 g/hp-hr for Class II engines. Low-emission engines were developed using three-way catalytic converters, passive secondary-air induction (SAI) systems, and in a couple of instances enleanment. Catalysts were integrated into the engine's mufflers, where feasible, to maintain a compact package. Due to the thermal sensitivity of these engines, carburetor calibrations were left unchanged in most cases, incorporating the stock rich settings. To enable HC oxidation under such rich conditions, a simple passive supplemental air induction system was developed. This system was then tuned to achieve the desired HC+NO_x reduction. Engines were then aged for either 250 hours (Class 1), or 500 hours (Class 2), with emission testing at intervals to track muffler-out emissions and catalyst performance. As shown in the figure below, results demonstrated that emissions from these engines could be significantly reduced. Except for the two Briggs and Stratton engines, all of the test engines achieved the target emission levels at the end of their useful lives.



Engine HC+NO_x Emissions at Useful Life

The main conclusions of this work are that catalyst technology can be successfully applied to small off-road engines; that such applications are durable; and that HC+NO_x reductions of 50 – 70% were demonstrated over the useful lives of several small engines. As shown below, catalysts used in this program performed well, withstanding the harsh environment of these small engines. The results of this program are significant because they show good catalyst performance can be achieved on small engines using the stock rich air/fuel calibration through the use of a novel supplementary air induction system.



Catalyst HC+NO_x Percent Conversion vs. Durability Hours

I. INTRODUCTION

The California Air Resources Board (CARB) contracted with Southwest Research Institute (SwRI[®]) to demonstrate useful-life durability of six low-emission developed small off-road engines (SORE). SOREs are a relatively high source of ozone forming pollutants in California, producing over 100 tons per day¹.

The objective of this program was to develop six non-handheld SOREs in low-emission configurations, and then age the engines through their useful lives. Four of the engines are used in walk-behind mower (WBM) applications, one is used in a riding mower, and one is used in constant-speed/generator applications. The goal was to reduce the tailpipe-out hydrocarbon (HC) plus oxides of nitrogen (NO_x) emissions to 50 percent or less of the current useful life standard of 12 g/hp-hr for Class I engines (65 cc < displacement < 225 cc), or 9 g/hp-hr for Class II engines (displacement ≥ 225 cc). Low-emission engines were developed using three-way catalytic converters, passive secondary-air induction (SAI) systems, and enleanment, when needed. Catalysts were provided by members of the Manufacturers of Emission Controls Association (MECA).

¹ Air Resources Board, "Staff Report: Public Hearing to Consider the Adoption of Exhaust and Evaporative Emission Control Requirements for Small Off-Road Equipment and Engines Less Than or Equal to 19 Kilowatts," September 2003.

II. DESCRIPTION OF PROGRAM

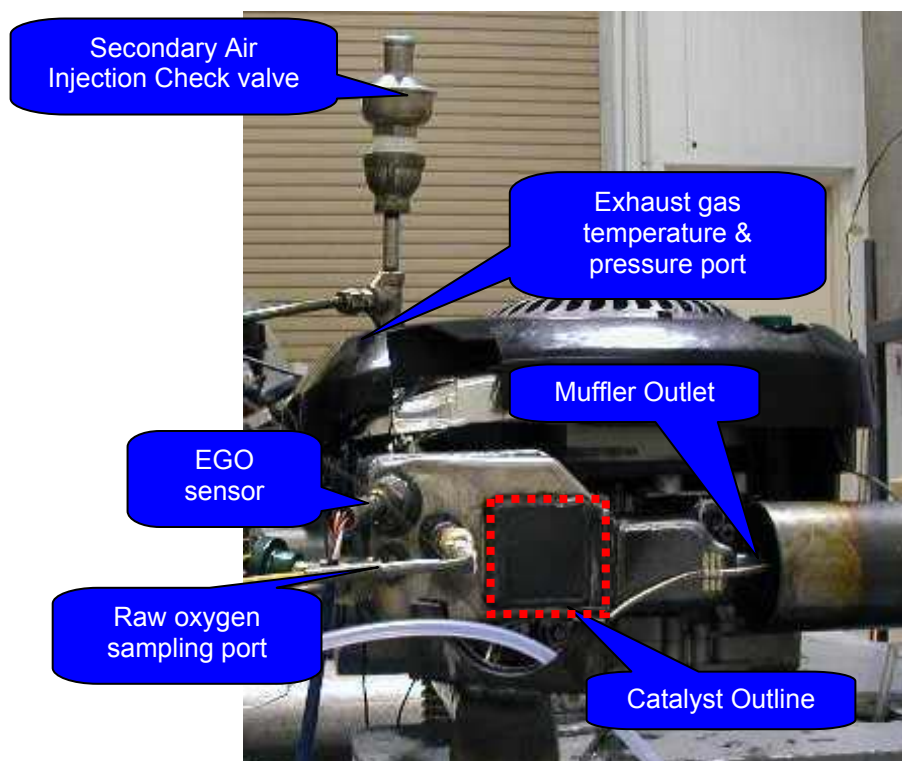
A. Project Engines

Six engines meeting current Tier II standards were selected by CARB, based on specifications such as application and market share. All engines are naturally aspirated, air-cooled, four-stroke, carbureted engines with an overhead valve train. All engines, with the exception of the Kawasaki, are single cylinder.

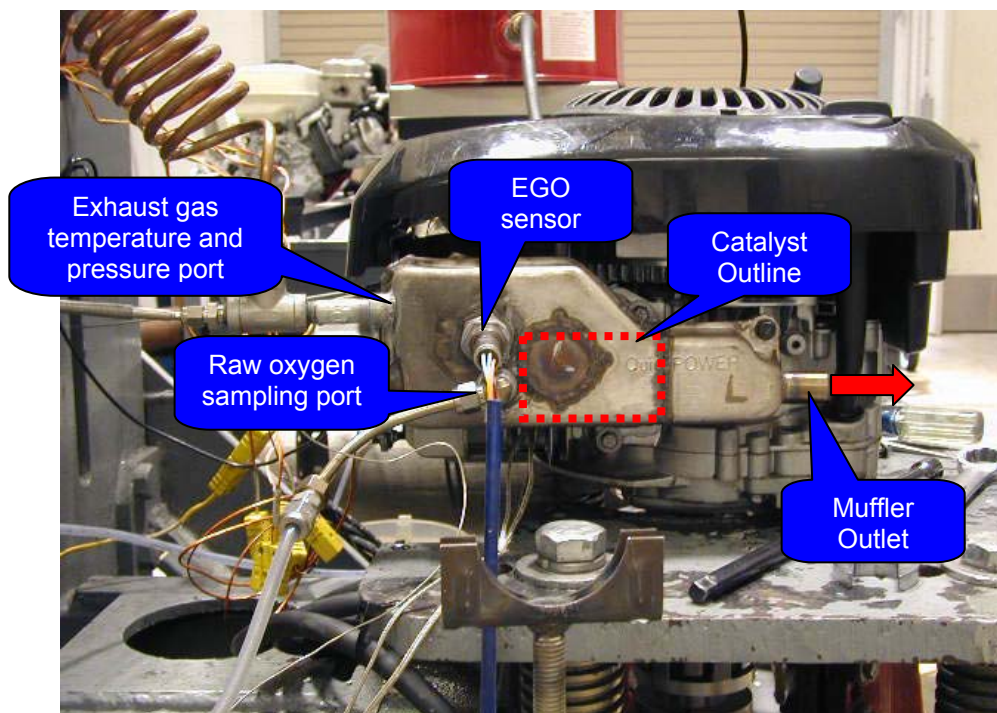
Originally, two identical Briggs and Stratton Intek engines were selected so that a comparison could be made between a high-loaded and a low-loaded catalyst for the same engine calibration. The needed catalysts, however, were not available in time to perform this experiment. Therefore, the second Briggs and Stratton engine was developed separately from the first engine, with an alternative catalyst and a more refined passive SAI system. Engines tested are shown in Figures 1 through 6.

TABLE 1. PROJECT ENGINES

Engine No.	Class	Mfg.	Appl.	Family/Model	Displacement, cc	Rated Power, hp
1	I	Briggs	WBM	YBSXS.1901VE Intek	190	6.5
2	I	Briggs	WBM	YBSXS.1901VE Intek	190	6.5
3	I	Tecumseh	WBM	YTPXS.1951AA OVRM 120	195	6.5
4	I	Honda	WBM	2HNXS.1611AK GCV160	160	5.5
5	II	Kawasaki	Riding Mower	YKAX6752QA FH601V	675	19
6	II	Honda	GEN	2HNXS.3892AK GX-340QA2	340	11



**FIGURE 1. BRIGGS AND STRATTON ENGINE NO.1
WITH CATALYST C INTEGRATED IN MUFFLER**



**FIGURE 2. BRIGGS AND STRATTON ENGINE NO. 2
WITH CATALYST L INTEGRATED IN MUFFLER**

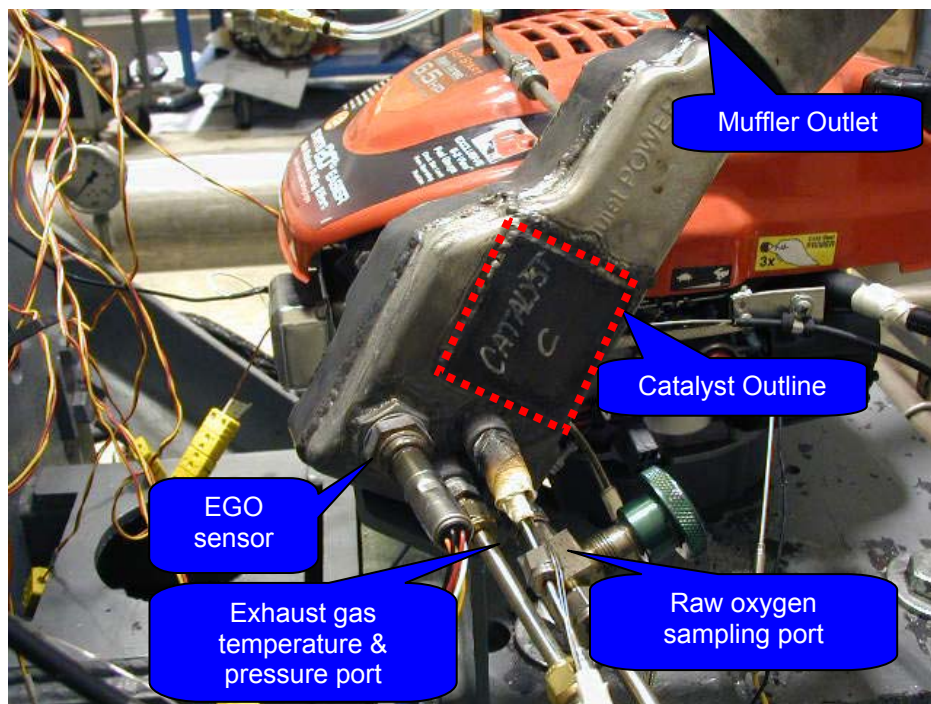


FIGURE 3. TECUMSEH OVRM120 ENGINE WITH CATALYST C INTEGRATED IN MUFFLER

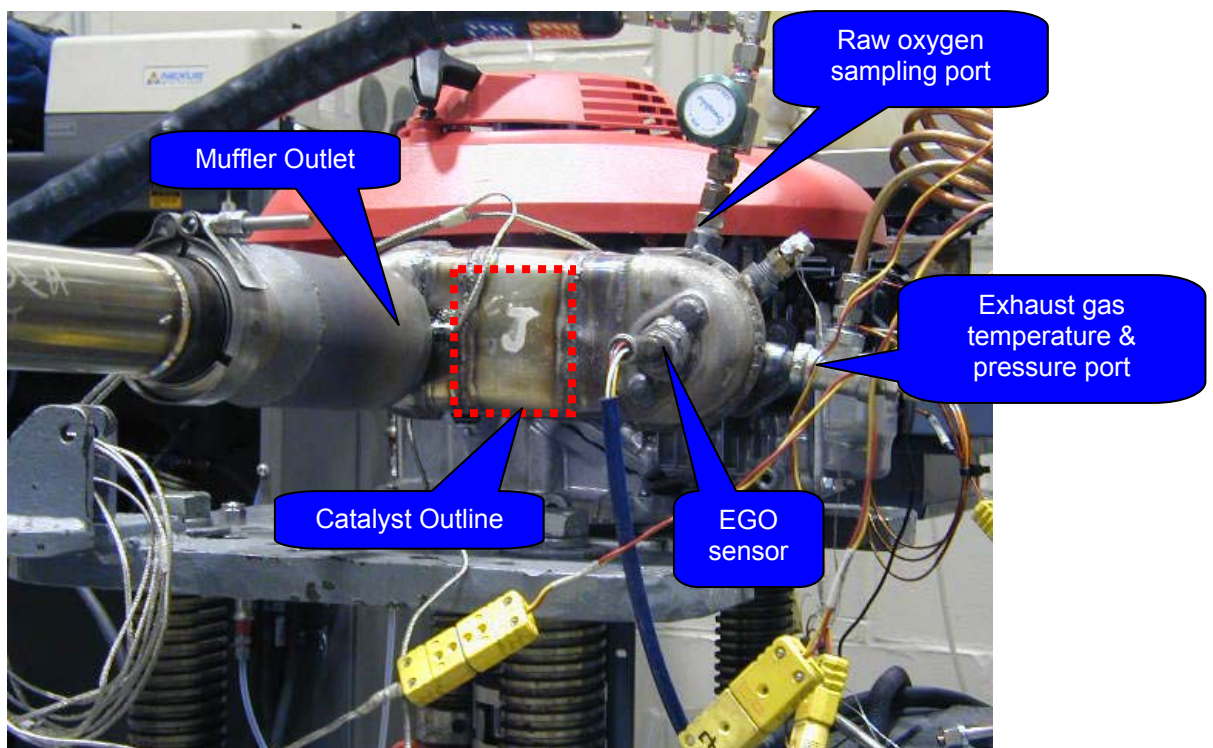


FIGURE 4. HONDA GCV160 ENGINE WITH CATALYST J INTEGRATED IN MUFFLER

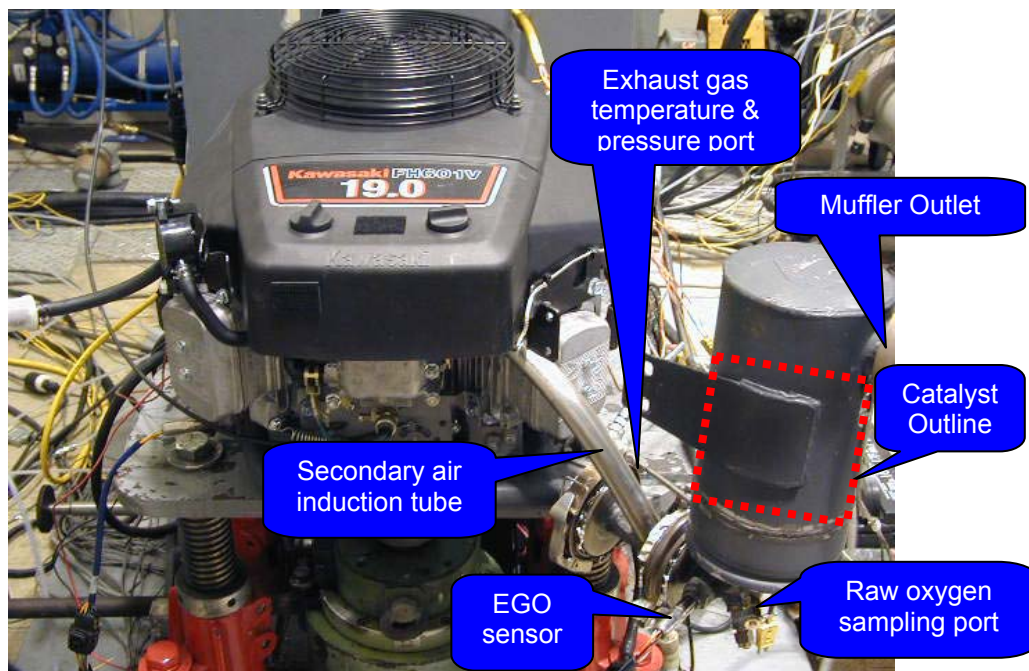


FIGURE 5. KAWASAKI FH601V ENGINE WITH CATALYST E INTEGRATED IN MUFFLER

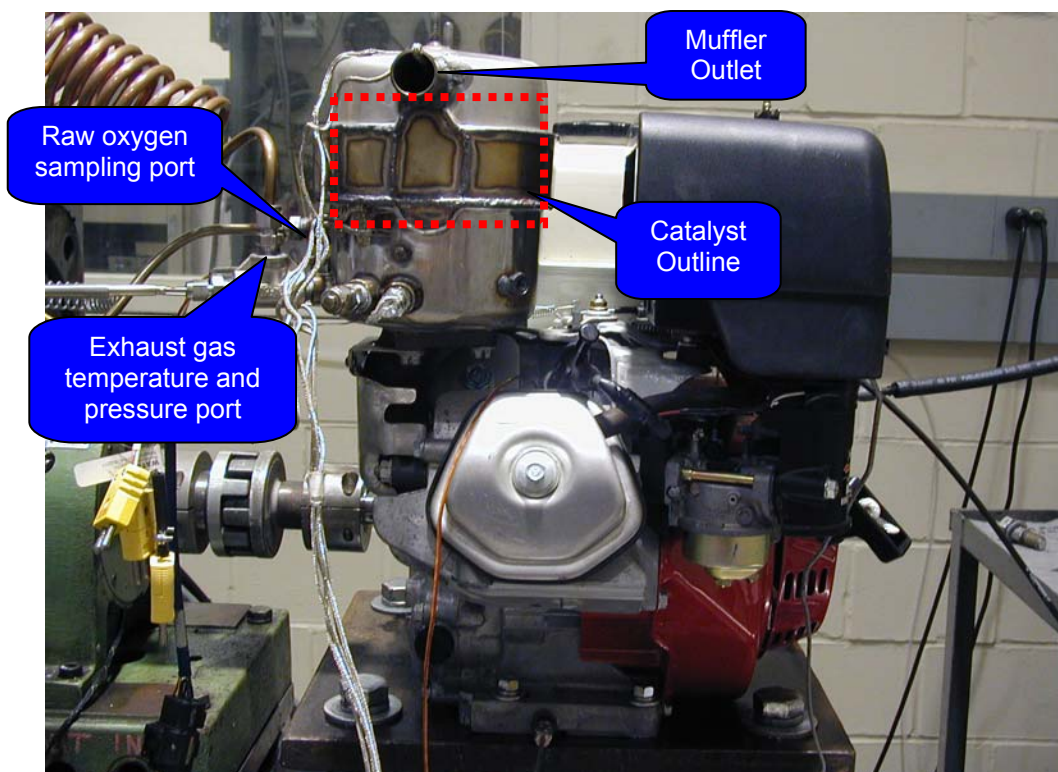


FIGURE 6. HONDA GX340 ENGINE WITH CATALYST I2 INTEGRATED IN MUFFLER

Table 2 outlines the duty cycle for the Class I walk-behind mower engines, which use an intermediate speed of 3060 RPM for testing. The California and federal small engine test cycle for generators is a rated speed 6-mode cycle, which includes idle. The Honda generator was also tested over the 6-mode intermediate speed cycle. Table 3 outlines the duty cycle for generator engines, which run at a rated speed of 3600 RPM. For this program, the Briggs and Stratton engines used a 5-mode duty cycle with an intermediate speed of 3060 RPM consistent with manufacturers' certification procedures, as shown in Table 4.

**TABLE 2. CARB 6-MODE SORE TEST CYCLE
(TECUMSEH OVRM120, HONDA GCV160, AND KAWASAKI FH601V)**

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Speed (% rated)	85	85	85	85	85	Idle
Load (%)	100	75	50	25	10	0
Weight Factor (%)	9	20	29	30	7	5

TABLE 3. GENERATOR TEST CYCLE (HONDA GX340)

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Speed (% rated)	100	100	100	100	100	Idle
Load (%)	100	75	50	25	10	0
Weight Factor (%)	9	20	29	30	7	5

TABLE 4. TEST CYCLE USED FOR BRIGGS AND STRATTON ENGINES

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Speed (% rated)	85	85	85	85	85
Load (%)	100	75	50	25	10
Weight Factor (%)	9	21	31	32	7

Engines were operated repetitively using the above test cycles to age the engines through their useful lives. Durability modes were run based on the modal weight percentage over one-hour. The Briggs and Stratton, Tecumseh, and Honda GCV160 engines were aged for 250 hours with emissions testing performed at 0, 125, and 250 hours. The Kawasaki and Honda GX340 engines were aged for 500 hours with emissions testing at 0, 125, 250, and 500 hours.

B. Project Catalysts

At the beginning of the program, participating MECA members were each assigned an engine for which they were to provide a three-way catalyst (TWC). Catalysts were chosen by manufacturers based on prior small off-road engine experience, program objectives, and data specific to each engine. Actual test data, including exhaust temperatures, baseline air-fuel ratios, and mass emission rates were

not available at the time of catalyst selection. Table 5 outlines the catalysts that were used in final, developed configurations. All catalysts are of three-way formulation with metallic substrates. An attempt was made to integrate all of the catalysts in modified stock mufflers for their respective engines. All catalysts used, with the exception of catalyst I2, were the exact substrates supplied by MECA members. Catalyst I2 was a modified part, having a 68 mm diameter core cut-out of a larger 118 mm diameter by 65 mm long substrate using a water knife. This catalyst was canned by SwRI using a set of Z-seals, a ¼ inch intumescent mat, and a set of retaining rings. Figures 7 through 16 show the selected catalysts.

TABLE 5. CATALYSTS USED IN FINAL DEVELOPMENT CONFIGURATIONS FOR SMALL OFF-ROAD ENGINES

Engine	Catalyst ID	Diameter, mm	Length, mm	Cell Density, cpsi
Briggs and Stratton No. 1	C	60.0	50.8	200
Briggs and Stratton No. 2	L	39.2	50.0	400
Tecumseh OVRM120	C	60.0	50.8	200
Honda GCV160	J	60.0	50.8	400
Kawasaki FH601V	E	118	115	400
Honda GX340	I2	68.0	65.0	600

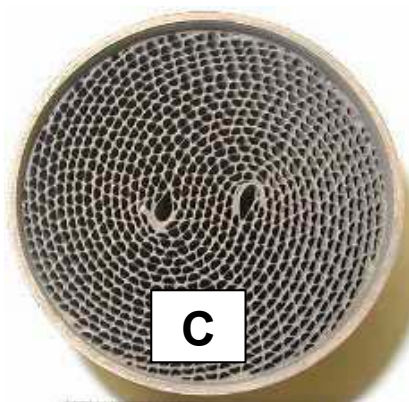


FIGURE 7. CATALYST C (CROSS-SECTIONAL VIEW)

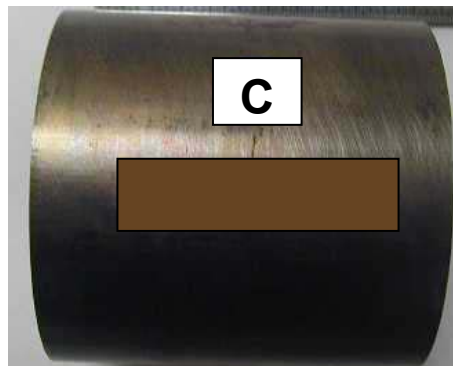


FIGURE 8. CATALYST C (AXIAL VIEW)

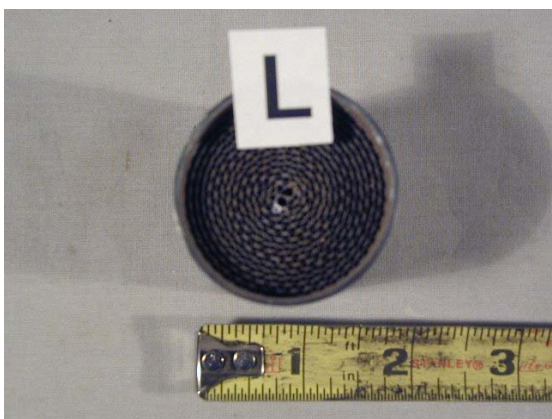


FIGURE 9. CATALYST L (CROSS-SECTIONAL VIEW)



FIGURE 10. CATALYST L (AXIAL VIEW)

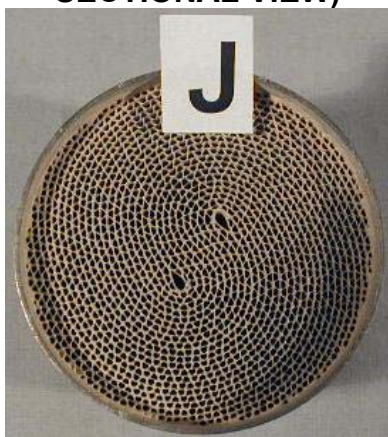


FIGURE 11. CATALYST J (CROSS-SECTIONAL VIEW)



FIGURE 12. CATALYST J (AXIAL VIEW)

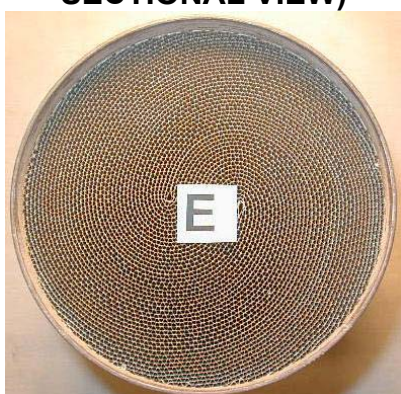


FIGURE 13. CATALYST E (CROSS-SECTIONAL VIEW)



FIGURE 14. CATALYST E (AXIAL VIEW)

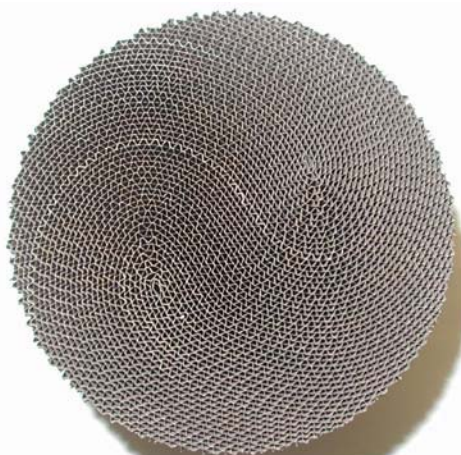


FIGURE 15. CATALYST I2 (CROSS-SECTIONAL VIEW)



FIGURE 16. CATALYST I2 (AXIAL VIEW)

C. Exhaust Emissions Development

Emissions development was performed in several steps. After an engine was run-in for two-hours and baseline emission tested, a suitable catalyst was coupled to the engine to observe the performance of the system with “bolt-on” aftertreatment. Next, a controlled amount of air was injected into the exhaust system upstream of the catalyst. Since these engines all employ rich, base calibrations, additional air was needed to achieve the target HC reduction level. If the catalyst was able to meet the emission reduction target, a passive secondary-air induction system was developed. When necessary, enleanment was used to further enhance catalyst activity.

The passive SAI system used the venturi principle to add supplemental air upstream of the catalyst, without connection to an external air supply. A schematic of the passive SAI system is shown in Figure 17. Similar SAI systems were incorporated on the first and second Briggs and Stratton, Tecumseh, Kawasaki, and Honda GCV160 engines. The SAI system is designed to capture air circulated above the engine from the flywheel impeller, and direct it into the exhaust pipe through the use of a transfer tube and dampening chamber. The dampening chamber traps exhaust that escapes the SAI orifices, and allows it to be mixed with fresh air from the flywheel impeller, thereby redirecting it into the exhaust. To reduce exhaust scavenging through the orifices, a venturi is designed into the pipe to create a low-pressure region. Figure 18 shows the SAI system on the Tecumseh engine.

For the Kawasaki and first Briggs and Stratton engines, sufficient emission reductions were not achievable with baseline engine calibrations because the engines were running too rich. These engines were conservatively enleaned to achieve higher catalyst performance, adhering to manufacturer recommended guidelines for safe operation. Figure 19 shows the zero-hour air-fuel ratio profiles of the six engines tested in baseline and low-emission developed configurations. No enleanment was utilized on the second Briggs, Tecumseh, Honda GCV160, or Honda GX340 engines.

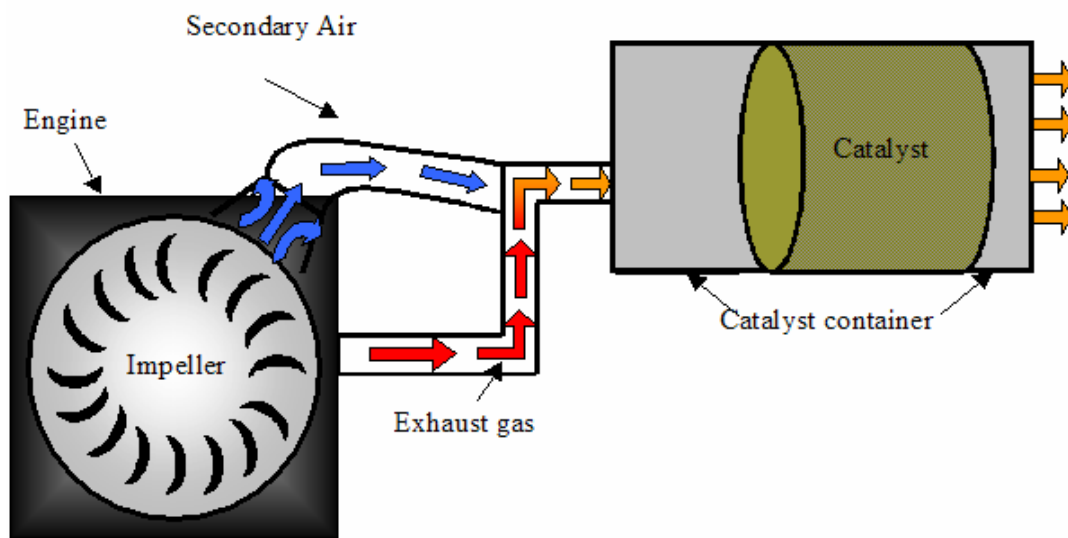


FIGURE 17. SCHEMATIC OF DEVELOPED PASSIVE SAI SYSTEM

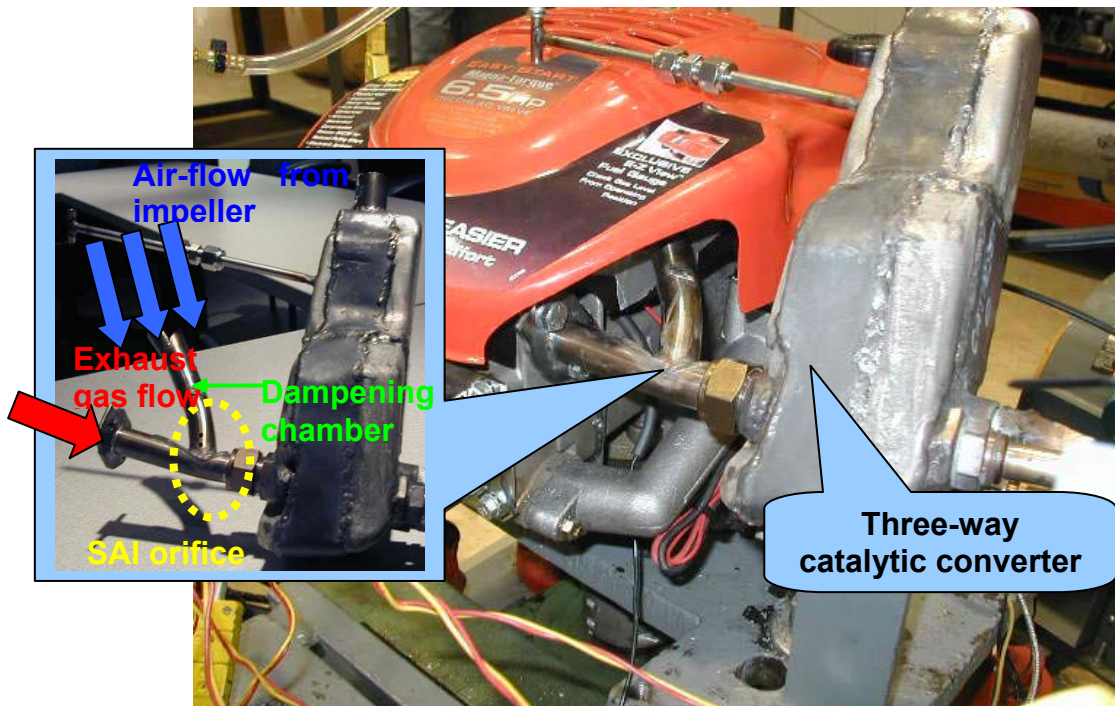


FIGURE 18. PASSIVE SAI SYSTEM ON TECUMSEH OVRM120 ENGINE

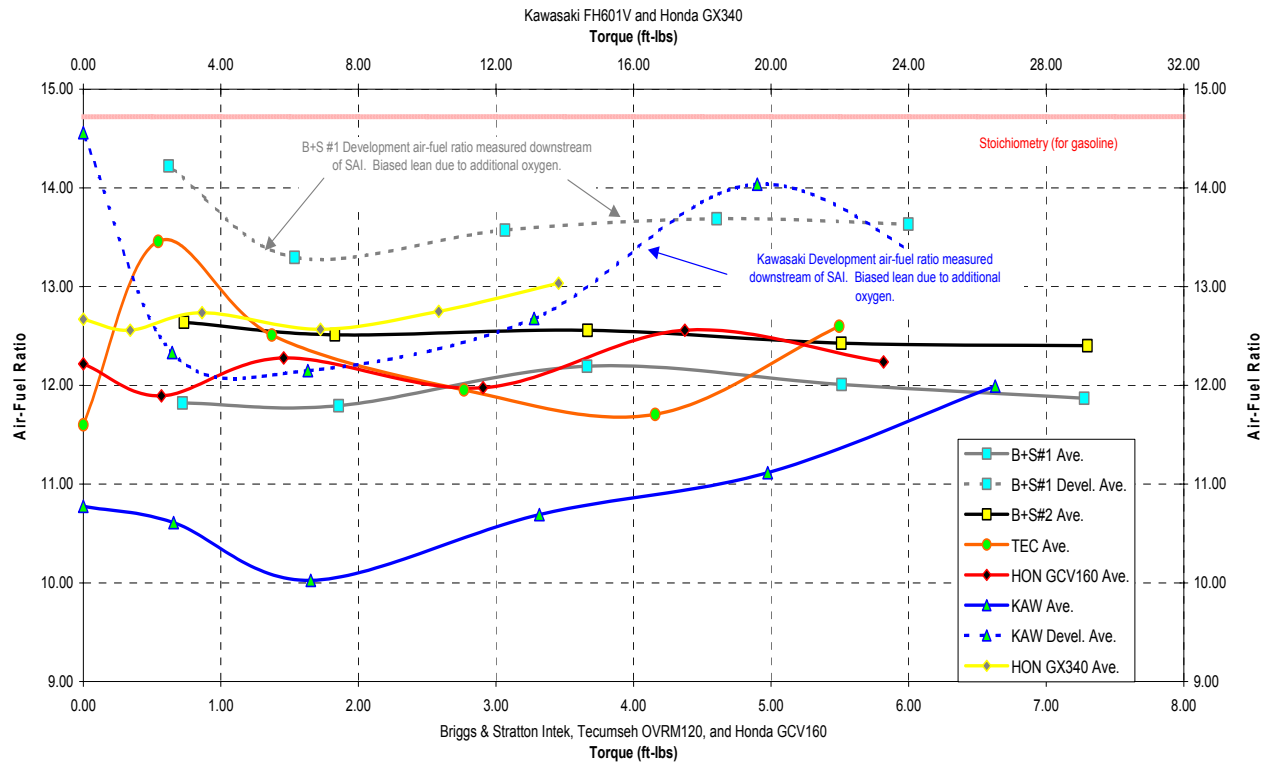


FIGURE 19. AVERAGE BASELINE AND DEVELOPED AIR-FUEL RATIOS OF SMALL OFF-ROAD ENGINES

Figures 20 through 31 are included to help capture the location of temperature measurements for the developed engine configurations.

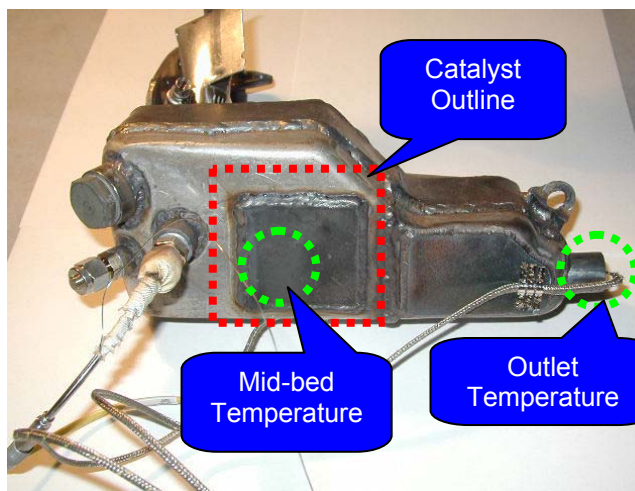


FIGURE 20. FRONT-VIEW OF B+S NO. 1 EXHAUST SYSTEM

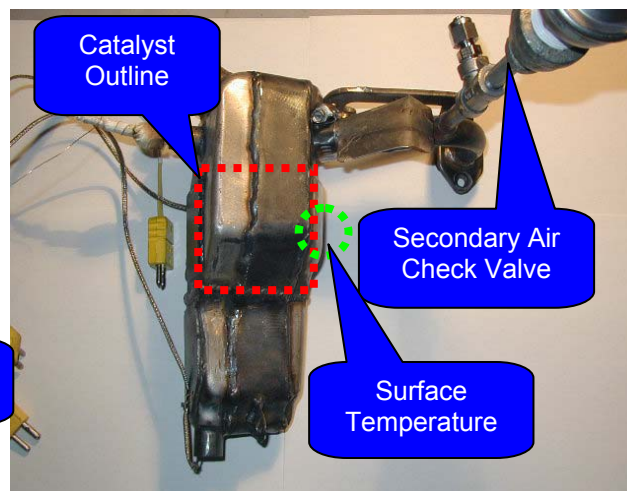


FIGURE 21. TOP-VIEW OF B+S NO. 1 EXHAUST SYSTEM

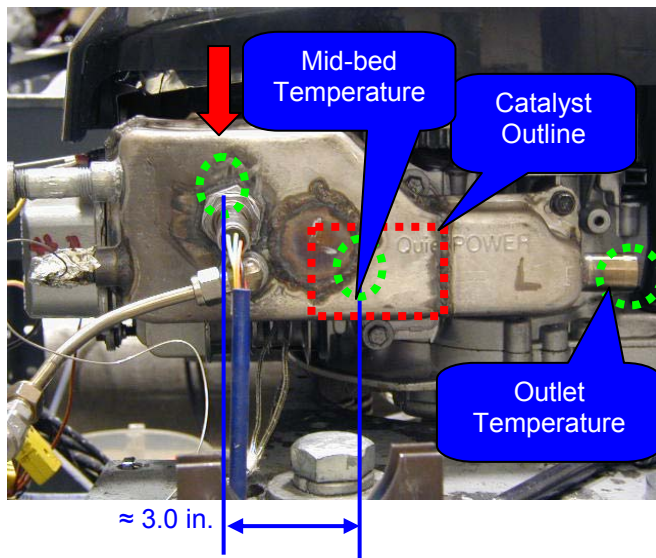


FIGURE 22. FRONT-VIEW OF B+S NO. 2 EXHAUST SYSTEM

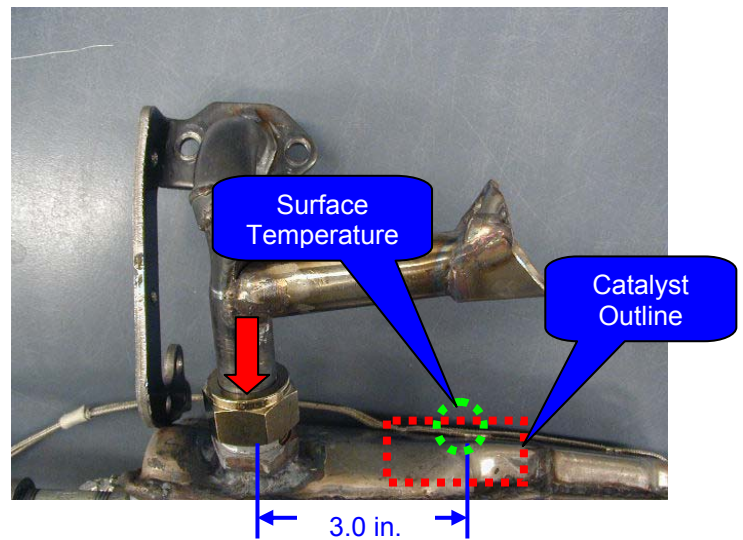


FIGURE 23. REAR-VIEW OF B+S NO. 2 EXHAUST SYSTEM

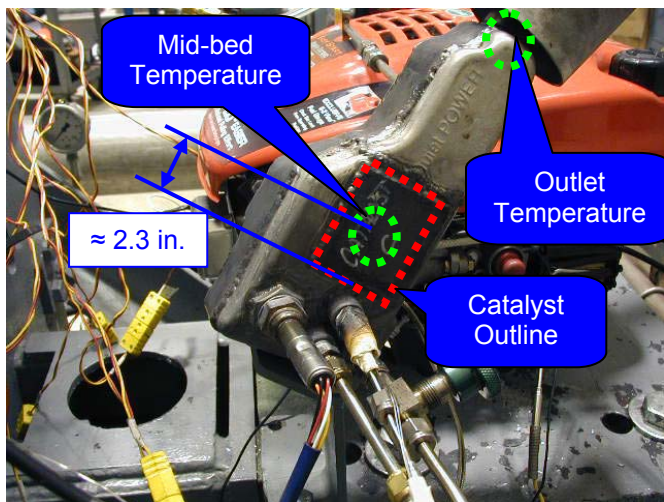


FIGURE 24. FRONT-VIEW OF TECUMSEH OVRM120 EXHAUST SYSTEM

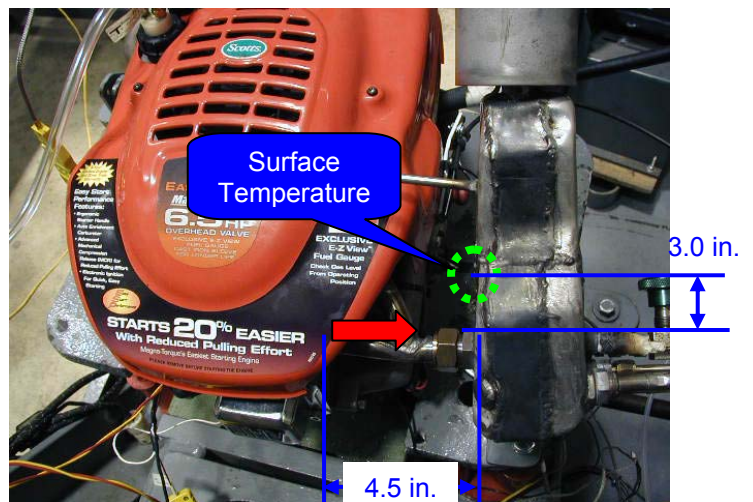


FIGURE 25. SIDE-VIEW OF TECUMSEH OVRM 120 EXHAUST SYSTEM

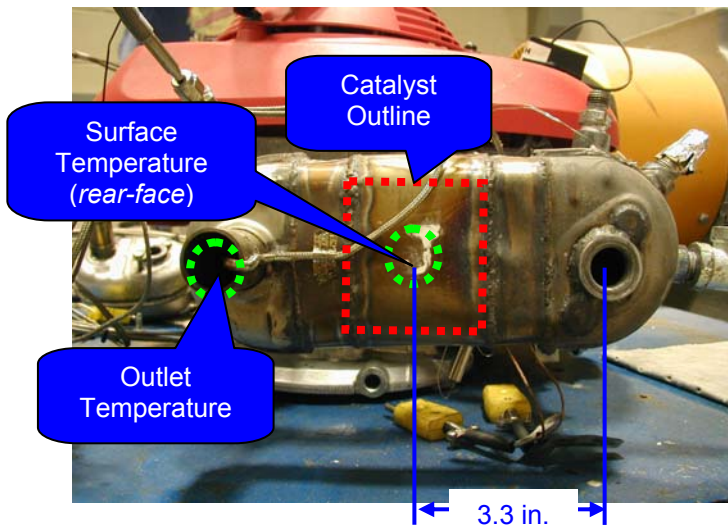


FIGURE 26. FRONT-VIEW OF HONDA GCV160 EXHAUST SYSTEM

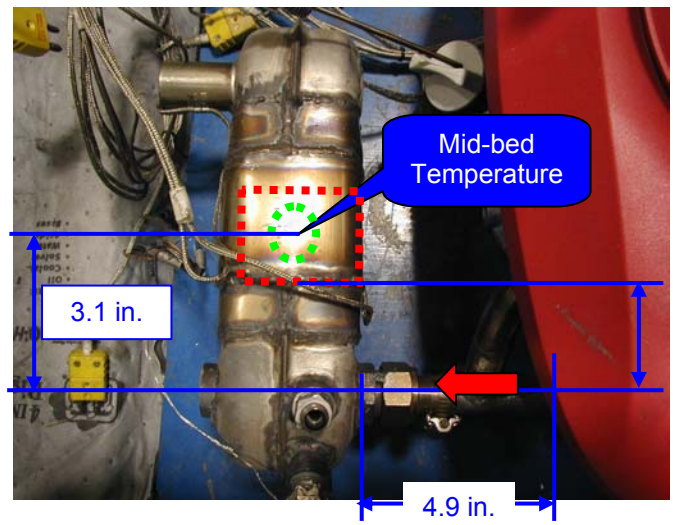


FIGURE 27. TOP-VIEW OF HONDA GCV160 EXHAUST SYSTEM

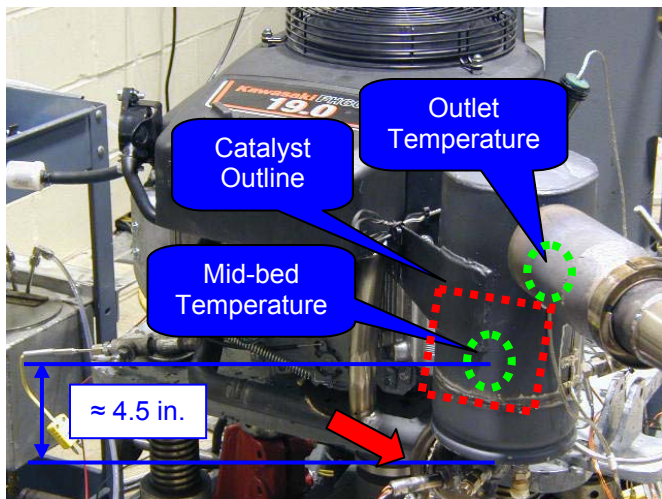


FIGURE 28. OFFSET/FRONT-VIEW OF KAWASAKI FH601V EXHAUST SYSTEM

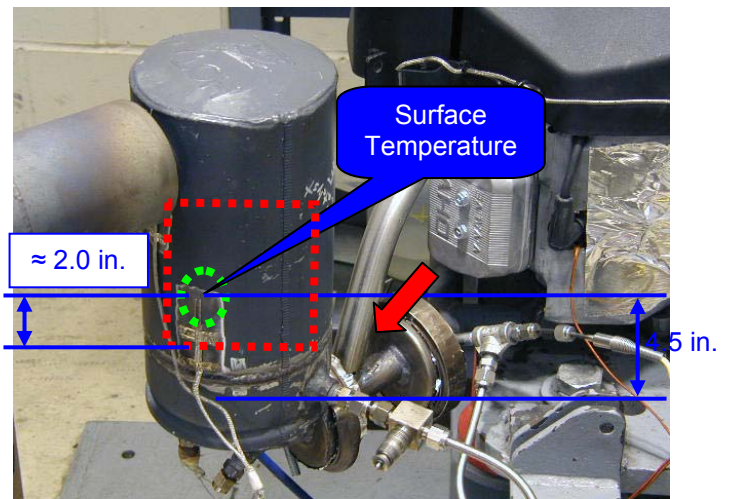


FIGURE 29. SIDE-VIEW OF KAWASAKI FH601V EXHAUST SYSTEM

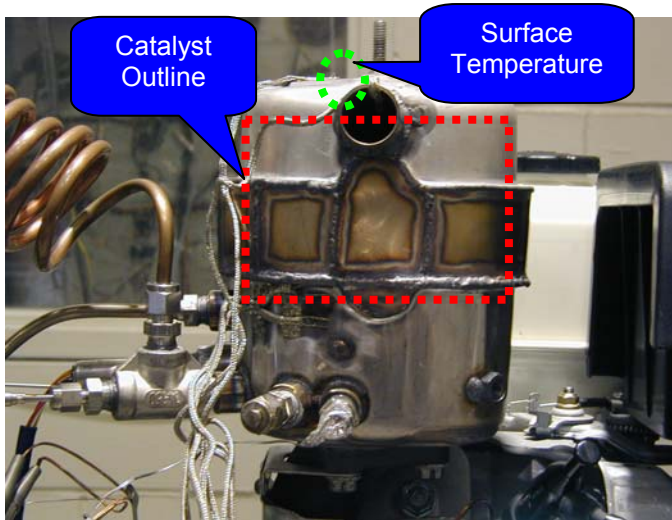


FIGURE 30. FRONT-VIEW OF HONDA GX340 EXHAUST SYSTEM

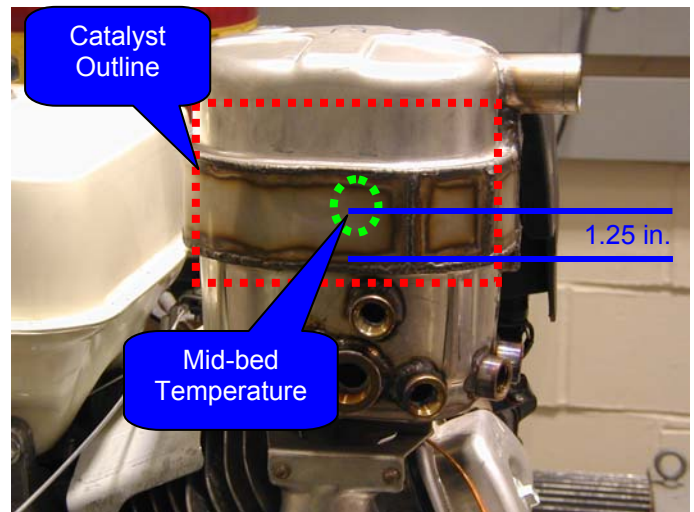


FIGURE 31. SIDE-VIEW OF HONDA GX340 EXHAUST SYSTEM

D. Emissions Testing

Emissions testing was performed on the Department of Emissions Research (DER) small off-road engine test stand. It includes a 20-hp eddy-current dynamometer on a movable stand that can accommodate both horizontal and vertical-shaft engines. Emissions measurement was performed using a Horiba MEXA 7200D 4-gas emissions bench. Hydrocarbon emissions were measured using a multi-range heated flame ionization detector (HFID), oxides of nitrogen (NO_x) were measured using a chemiluminescent analyzer, and carbon monoxide (CO) and carbon dioxide (CO_2) emissions were measured using non-dispersive infrared analyzers (NDIR). Exhaust was collected using an 8-inch dilution tunnel with bag sampling of diluted exhaust. Bags were sampled after each mode.

All emissions testing was performed with the same batch of California Phase II gasoline. Table 6 presents the properties of the fuel used.

TABLE 6. CALIFORNIA PHASE II GASOLINE FUEL PROPERTIES (EM-4749-F)

Fuel Property	Method	Phase II RFG
Specific Gravity	ASTM D4052	0.7383
Aromatics, vol.%	ASTM D1319	23.9
Olefins		4.8
Saturates		60.4
Carbon, wt.%	ASTM D5291	84.29
Hydrogen, wt.%		13.31
Nitrogen Content (ppm)	ASTM D4629	4.9
RON	ASTM D2699	96.6
MON	ASTM D2700	87.5
Oxygenates	ASTM D4815	
tBa-vol%		0.06
tBa-wt%		0.06
MTBE-vol%		10.82
MTBE-wt%		10.95
Distillation, °F	ASTM D86	
IBP		101
10%		136
20%		155
30%		171
40%		187
50%		205
60%		223
70%		241
80%		263
90%		298
FBP		377
Recovery, %		96.5
Residue, %		1.0
Loss, %		2.5

The Briggs and Stratton, Tecumseh, and Kawasaki user manuals recommend 30W engine oil for operation in the temperature range observed in the laboratory. For consistency, Briggs and Stratton 30W engine oil was used in these engines. The Honda engines were lubricated using a multi-grade oil, as specified in the user manuals. Table 7 shows the properties of the Briggs and Stratton and multi-grade oils.

TABLE 7. ENGINE OIL PROPERTIES

Oil Property	Method	Briggs and Stratton 30W engine oil	Castrol GTX 10W30 engine oil
Specific Gravity	ASTM D4052	0.88	0.87
Viscosity @ 25 °C, cSt	ASTM D455	202.16	156.19
Viscosity @ 40 °C, cSt	ASTM D455	85.78	73.35
Viscosity @ 100 °C, cSt	ASTM D455	11.00	11.05
Flash Point, °C (open cup)	ASTM D92	230	N/A
Total Base Number	ASTM D4739	6.53	6.03
Total Acid Number	ASTM D664	1.39	1.75
Carbon, mass %	ASTM D5291	85.09	85.18
Hydrogen, mass %		13.42	13.82
Ba, ppm	ASTM D5185	<1	<1
Ca, ppm		1231	1782
Mg, ppm		419	3
Mn, ppm		<1	<1
Na, ppm		516	<5
P, ppm		986	911
Zn, ppm		1038	964
Distillation by GC, °C	ASTM D6352		
IBP		284.9	308.8
10%		394.6	377.9
20%		417.4	399.5
30%		432.8	414.9
40%		446.9	427.1
50%		460.2	438.7
60%		474.8	450.1
70%		494.4	460.6
80%		545.7	472.0
90%		619.9	487.1
FBP		760.6	730.7

At zero-hours, the first Briggs and Stratton and Tecumseh engines were evaporative emissions tested in a vehicle SHED. Testing included a one-hour hot soak and a 24-hr. diurnal test. The engines were installed on their respective mowers and operated at the maximum level position for 15 minutes before placing them in the SHED for the hot soak tests. The diurnal test followed the vehicle test protocol. CARB discontinued testing of these prototype evaporative emissions control devices due to vapor leaks in the fuel tank cap.

E. Durability Testing

Engine service accumulation was performed at SwRI's Engine and Vehicle Research Division. The durability site included two 30-hp eddy current dynamometers. Each dynamometer was fully automated including safety system monitoring. Safeties were defined for certain engine parameters with automated engine shutdown. These parameters are listed in Table 8. Engines were fueled with California Phase II gasoline. With the exception of the first Briggs and Stratton and Tecumseh engines through 125 hours, maintenance was performed during the service accumulation periods according to manufacturer recommended procedures, including oil changes, air filter cleaning and replacement, and spark plug cleaning and replacement.

TABLE 8. PARAMETERS MONITORED FOR AUTOMATED SAFETY SHUTDOWN DURING DURABILITY

Engine Speed (RPM)
Cylinder Head Temperature (°F)
Oil Temperature (°F)
Exhaust Gas Temperature (°F)
Catalyst Mid-Bed Temperature (°F)

III. RESULTS AND DISCUSSIONS

A. Briggs and Stratton Intek Engine No. 1

Briggs and Stratton Engine No. 1 was baseline tested and then developed to a low-emissions configuration. During development, the engine showed signs of power loss and emissions deterioration. After inspection of the engine with Briggs and Stratton personnel, it was decided to continue to use the engine for the program. Baseline, engine-out, and fully developed emissions results are presented in Table 9. Individual test data sheets are presented in Appendix A.

The final low-emissions configuration incorporated catalyst C with a lean fixed carburetor jet (Jet No. 2-0.027 in.), and a passive secondary air induction system utilizing a 4-hole venturi and a check valve. The throat of the venturi was shrouded so a portion of the flywheel impeller cooling air was directed into the venturi throat. This augmented the supplemental air at the catalyst inlet, improving HC and CO conversion.

Figure 32 shows the exhaust pipe with the SAI system. The engine calibration change was conservative, remaining within the not-to-exceed engine operating limits defined by Briggs and Stratton. On average at zero-hours, the developed configuration generated 3.67 g/hp-hr HC, 0.47 g/hp-hr NO_x, and 91 g/hp-hr CO.

TABLE 9. BRIGGS AND STRATTON ENGINE NO. 1 EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Baseline Emissions								
B+S #1 BSLN5	4.24	None	Stock-fixed	7.88	NA	2.06	9.94	304
B+S #1 BSLN6	4.32	None	Stock-fixed	8.04	7.25	1.96	10.00	303
BSLN Ave.	4.28			7.96	7.25	2.01	9.97	304
Development Emissions (0-Hour)								
B+S #1 BSLN-JET #2	3.43	None	Fixed Jet No. 2	10.26	NA	4.46	14.73	224
B+S #1 CAT-C-STCK-JET	3.48	Cat. C	Stock-fixed	6.80	NA	0.18	6.98	229
B+S #1 CAT-C-BSLN3	3.59	Cat. C	Fixed Jet No. 2	3.48	2.96	0.40	3.88	86
B+S #1 CAT-C-BSLN4	3.48	Cat. C	Fixed Jet No.2	3.85	NA	0.55	4.40	96
CAT-C BSNL Ave.	3.54			3.67	2.96	0.48	4.14	91
125-hour Emissions								
B+S #1-125-BSLN	3.18	None	Fixed Jet No. 2	15.63	NA	4.73	20.35	235
B+S #1-125-STK-BSLN	3.25	None	Stock-fixed	17.46	NA	2.21	19.67	353
B+S #1-125-#1	3.16	Cat. C	Fixed Jet No. 2	7.27	6.33	0.85	8.12	144
B+S #1-125-#2	3.26	Cat. C	Fixed Jet No. 2	7.51	6.63	0.94	8.45	146
125 Cat.C Ave.	3.21			7.39	6.48	0.90	8.29	145
250-hour Emissions								
No 250-hour testing was performed on Briggs and Stratton engine no. 1								

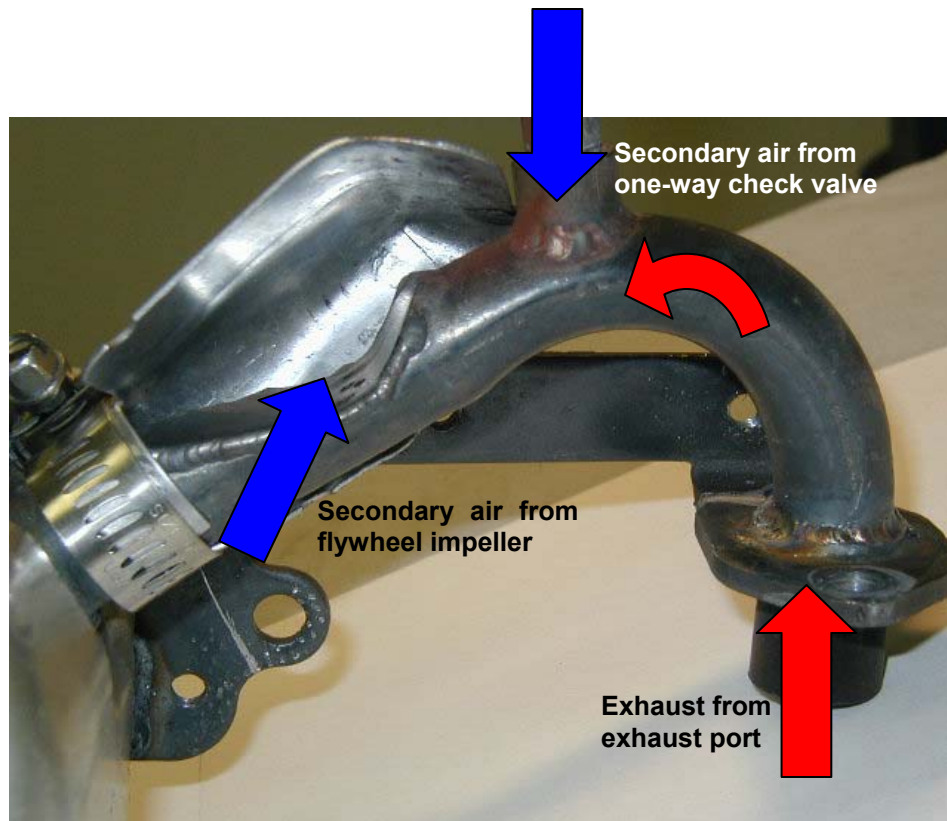


FIGURE 32. SECONDARY AIR INDUCTION SYSTEM ON BRIGGS AND STRATTON ENGINE NO. 1 MUFFLER

Figure 33 shows the zero-hour emissions of four configurations: baseline, stock carburetion with catalyst C and secondary air, engine-out with stock muffler and fixed jet No. 2, and fully developed configurations. Overall, HC+NO_x emissions were reduced by 58 percent, HC emissions by 54 percent, NO_x emissions by 76 percent, and CO emissions by 70 percent compared to the baseline configuration.

After completing the 125-hour service accumulation, the engine was emissions tested. During durability, the engine stopped running on ten separate occasions. After service checks were performed, the problem was determined to be caused by misfiring due to a bad spark plug. After a change of spark plug, the problem was no longer experienced. At 125 hours, the engine's stock-baseline emissions increased significantly from those at zero hours. Figure 34 presents a comparison between 0-hour and 125-hour emissions data. Engine-out (no catalyst) emissions significantly increased at 125-hours while catalyst performance held up reasonably well. The catalyst reduced HC+NO_x emissions by 70 percent at zero-hours and by 58 percent at 125 hours. The reduction in HC+NO_x conversion may be due to the increase of engine-out HC emissions and a lack of sufficient oxygen to completely oxidize these hydrocarbons. The misfire/engine shutdown episodes during durability may also have caused some loss in catalyst efficiency.

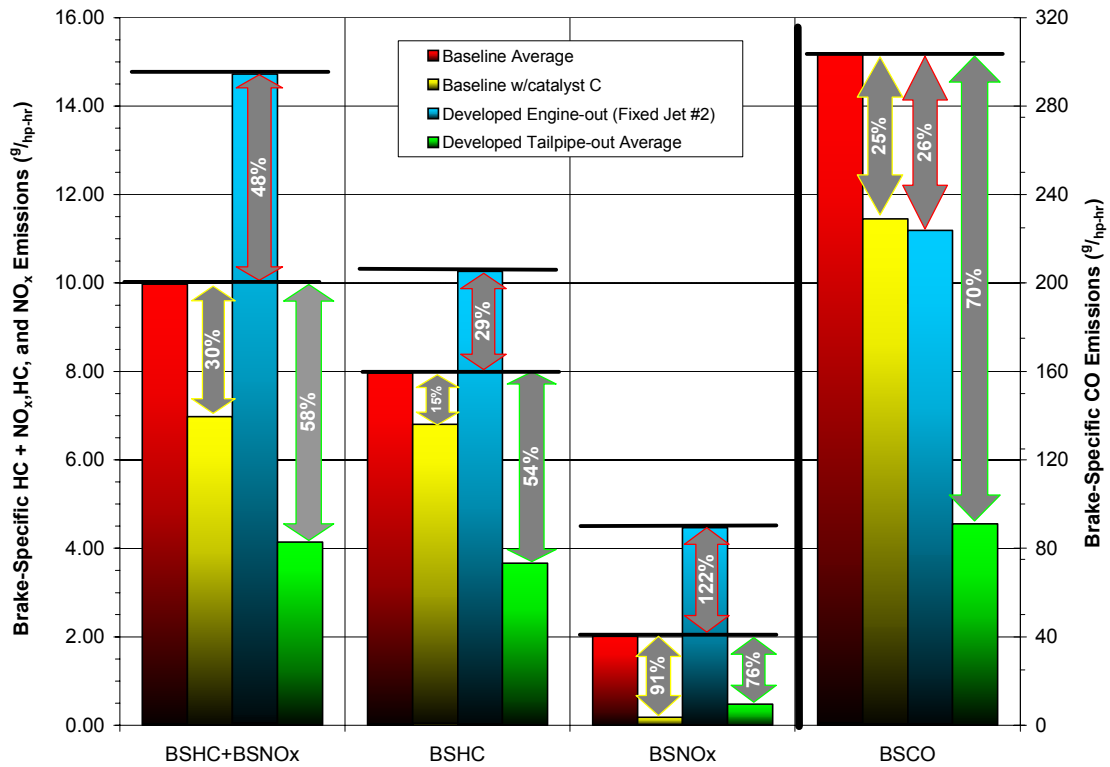


FIGURE 33. BRIGGS AND STRATTON ENGINE NO. 1-- ZERO-HOUR EMISSIONS

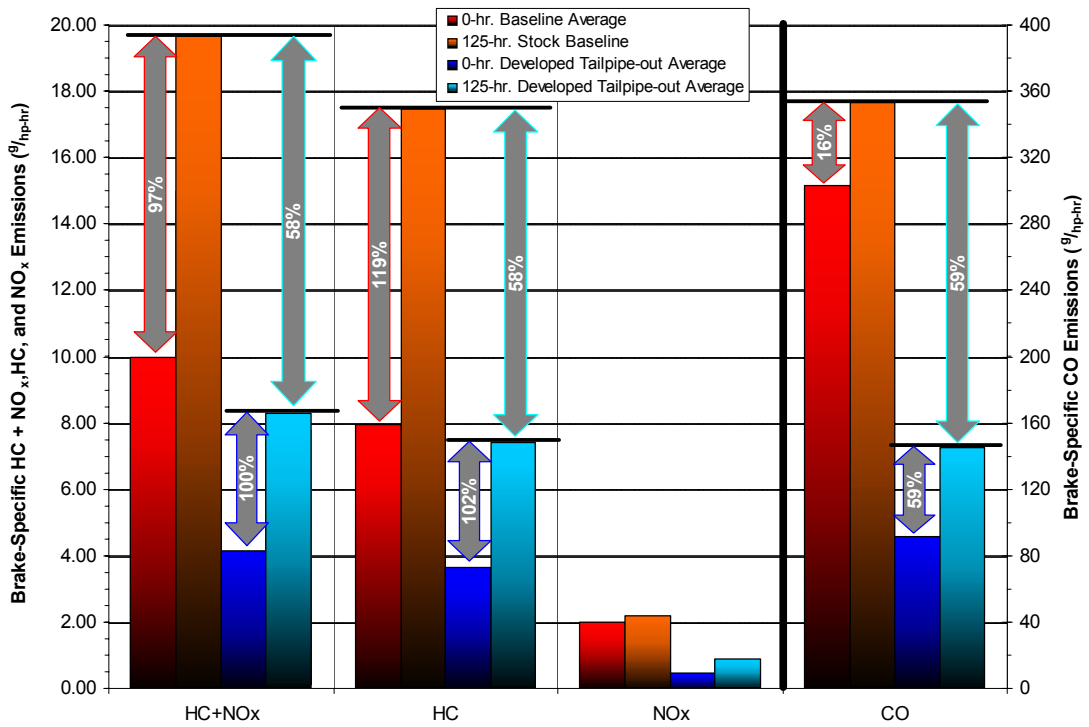


FIGURE 34. BRIGGS AND STRATTON ENGINE NO. 1-- ZERO-HOUR AND 125-HOUR EMISSIONS

After review of the 125-hour emissions data, CARB decided to remove Briggs and Stratton Engine No. 1 from the program due to engine deterioration. No additional emissions tests or durability was performed on this engine. From results presented in Table 9, a set of multiplicative deterioration factors (DF) was calculated for a useful life of 125 hours based on the standard least squares curve fit method and the equation below. The DFs are presented in Table 10 for the three different engine configurations.

$$DF = \frac{E_{UL}}{E_o}$$

E_{UL} = Useful life emission level calculated from least squares trendline equation

E_o = Baseline emission level of stabilized engine

TABLE 10. CALCULATED DETERIORATION FACTORS FOR BRIGGS AND STRATTON ENGINE NO. 1 THROUGH 125 HOURS

Configuration	0-Hour Test No.	125-Hour Test No.	Deterioration Factors			
			HC+NO _x	HC	NO _x	CO
Engine-Out	B+S #1 BSLN-JET # 2	B+S #1-125-BSLN	1.38	1.52	1.06	1.05
Developed	B+S #1 CAT-C-BSLN3 & 4	B+S #1-125-#1 & #2	2.00	2.02	1.87	1.59

B. Briggs and Stratton Intek Engine No. 2

Briggs and Stratton Engine No. 2 was baseline tested following baseline testing of the first Briggs and Stratton engine. Table 11 shows emission results for Briggs and Stratton Engine No. 2. During original baseline testing, Engine No. 2 emitted 19 percent less HC+NO_x emissions than Engine No.1. Due to the need to develop the remaining engines, Briggs Engine No. 2 was not developed until later in the program. During the development, it was noticed that stock-baseline emissions had increased significantly even though the engine had not been operated. It is believed that this may have been due the formation of combustion chamber deposits as a result of oil saturating the cylinder wall during storage. This can occur if an engine is stored on an incline causing oil to settle in the combustion. Due to the increase in stock 0-hr emissions, the engine was re-tested in the stock configuration to establish a new baseline. Zero-hour emission results are shown in Figure 35. Individual test data sheets are presented in Appendix B.

Development of Briggs and Stratton engine No. 2 followed baseline testing. The final developed configuration incorporated 400 cpsi catalyst L (39.2 mm in diameter by 50.0 mm long) integrated inside of a modified muffler, a passive SAI system designed into the neck of the exhaust pipe, and stock carburetion. On average, the developed configuration produced 4.09 g/hp-hr HC+NO_x, 3.70 g/hp-hr HC, 0.39 g/hp-hr NO_x, and 219 g/hp-hr CO. The development of this engine did not include modifying the engine's calibration. The final developed configuration reduced baseline emissions by 57 percent for HC+NO_x, 52 percent for HC, 79 percent for NO_x, and 29 percent for CO. Figure 35 compares emissions for the configurations tested on the second Briggs and

Stratton engine, including stock-baseline, stock-baseline with catalyst L (without SAI), and the final developed configuration.

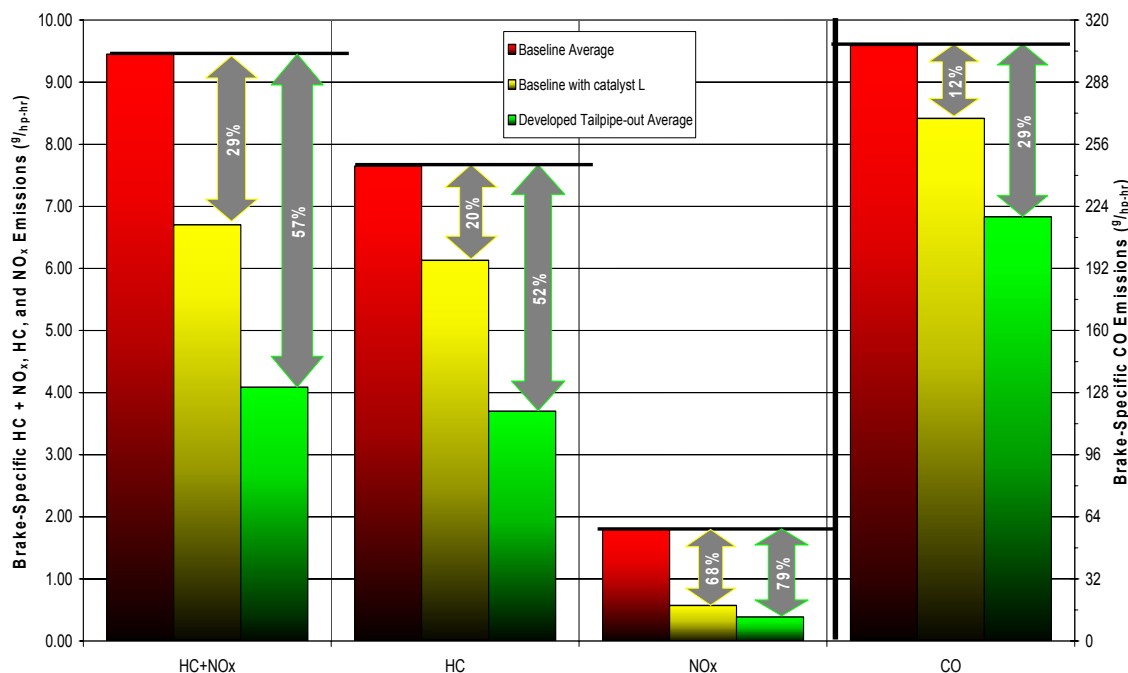


FIGURE 35. BRIGGS AND STRATTON ENGINE NO. 2 -- ZERO-HOUR EMISSIONS

After completing the 125-hour service accumulation, the engine was emissions tested. Scheduled maintenance was performed throughout aging, including oil changes, air filter cleanings, and spark plug checks. At 125 hours, the stock configuration produced an average of 14.7 g/hp-hr HC+NO_x, 12.8 g/hp-hr HC, 1.92 g/hp-hr NO_x, and 330 g/hp-hr CO, resulting in a 56 percent HC+NO_x increase compared to stock 0-hour results. On average, the developed configuration produced 8.17 g/hp-hr HC+NO_x, 7.58 g/hp-hr HC, 0.59 g/hp-hr NO_x, and 287 g/hp-hr CO, resulting in an HC+NO_x reduction of 44 percent from 125-hour engine-out emissions. Stock emissions increased significantly from zero-hour results due mainly to an increase of HC emissions. This may be due to loss of compression, improper valve seating, or other engine problems.

After completing the 250-hour service accumulation, the engine was emissions tested. Scheduled maintenance was performed throughout aging, including oil changes, air filter cleanings, and spark plug checks. At 250 hours, the stock configuration produced an average of 16.1 g/hp-hr HC+NO_x, 13.9 g/hp-hr HC, 2.24 g/hp-hr NO_x, and 290 g/hp-hr CO, resulting in a 70 percent HC+NO_x increase compared to stock 0-hour results. On average, the developed configuration produced 9.81 g/hp-hr HC+NO_x, 8.98 g/hp-hr HC, 0.83 g/hp-hr NO_x, and 260 g/hp-hr CO, resulting in an HC+NO_x reduction of 39 percent from 250-hour engine-out emissions. At 250 hours, HC+NO_x emissions from the developed configuration were 4 percent higher than 0-hour baseline emissions. HC+NO_x emissions at each interval are graphically presented in Figure 36. At 250 hours, catalyst efficiency is on the order of 39 percent for HC+NO_x, 35 percent for HC, 63 percent for NO_x, and 10 percent for CO. Figures 37 and 38 plot

the emission levels of the stock and developed configurations at each interval to calculate the deterioration factors for the second Briggs and Stratton engine. DFs are presented in Table 12. Increased HC emissions due to the deterioration of Briggs and Stratton Engine No. 2 is similar to that reported on other Briggs and Stratton engines².

TABLE 11. BRIGGS AND STRATTON ENGINE NO. 2 EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Original Baseline Emissions								
B+S #2 BSLN1	4.31	None	Stock-fixed	6.75	NA	1.48	8.23	326
B+S #2 BSLN2	4.29	None	Stock-fixed	6.64	NA	1.62	8.26	322
B+S #2 BSLN3	4.35	None	Stock-fixed	6.08	5.30	1.67	7.75	312
BSLN Ave.	4.32			6.49	5.30	1.59	8.08	320
Re-Established Baseline Emissions								
B+S #2-BSLN-RPT #3	4.23	None	Stock-fixed	7.99	NA	1.86	9.85	319
B+S #2-BSLN-RPT #4	4.43	None	Stock-fixed	7.30	6.41	1.75	9.05	295
NEW BSLN Ave.	4.33			7.65	6.41	1.80	9.45	307
Development Emissions (0-Hour)								
B+S #2-L-BSLN #1*	4.24	Cat. L	Stock-fixed	6.13	NA	0.57	6.70	269
B+S #2-L-#3	4.37	Cat. L	Stock-fixed	3.71	2.96	0.37	4.08	220
B+S #2-L-#4	4.45	Cat. L	Stock-fixed	3.69	NA	0.41	4.10	218
0 Cat. C Ave.	4.41			3.7	2.96	0.39	4.09	219
125-hour Emissions								
B+S #2-125-L-#1	3.73	Cat. L	Stock-fixed	7.79	6.67	0.55	8.34	283
B+S #2-125-L-#2	3.80	Cat. L	Stock-fixed	7.36	NA	0.63	7.99	291
125 Cat. L Ave.	3.77			7.58	6.67	0.59	8.17	287
B+S #2-125-STK-#1	3.96	None	Stock-fixed	12.73	11.49	1.90	14.63	330
B+S #2-125-STK-#2	4.03	None	Stock-fixed	12.83	NA	1.93	14.77	331
125 STK Ave.	4.0			12.78	11.49	1.92	14.7	331
250-hour Emissions								
B+S #2-250-L-#1	3.86	Cat. L	Stock-fixed	9.09	7.90	0.82	9.91	263
B+S #2-250-L-#2	3.90	Cat. L	Stock-fixed	8.87	NA	0.83	9.70	257
250 Cat L Ave.	3.88			8.98	7.90	0.83	9.81	260
B+S #2-250-STK-#1	4.08	None	Stock-fixed	13.94	12.68	2.20	16.14	292
B+S #2-250-STK-#2	4.11	None	Stock-fixed	13.78	NA	2.27	16.05	288
250 STK Ave.	4.10			13.86	12.68	2.24	16.10	290
* Catalyst testing without secondary air								

² Reisel, J.R., Schmitt, A., and Ouradnik, Z., "Investigation of the Source of Increased Hydrocarbon Emissions Over the Life Cycles of Small Utility Engines," SAE 2003-32-0022, Madison, WI, September 2003.

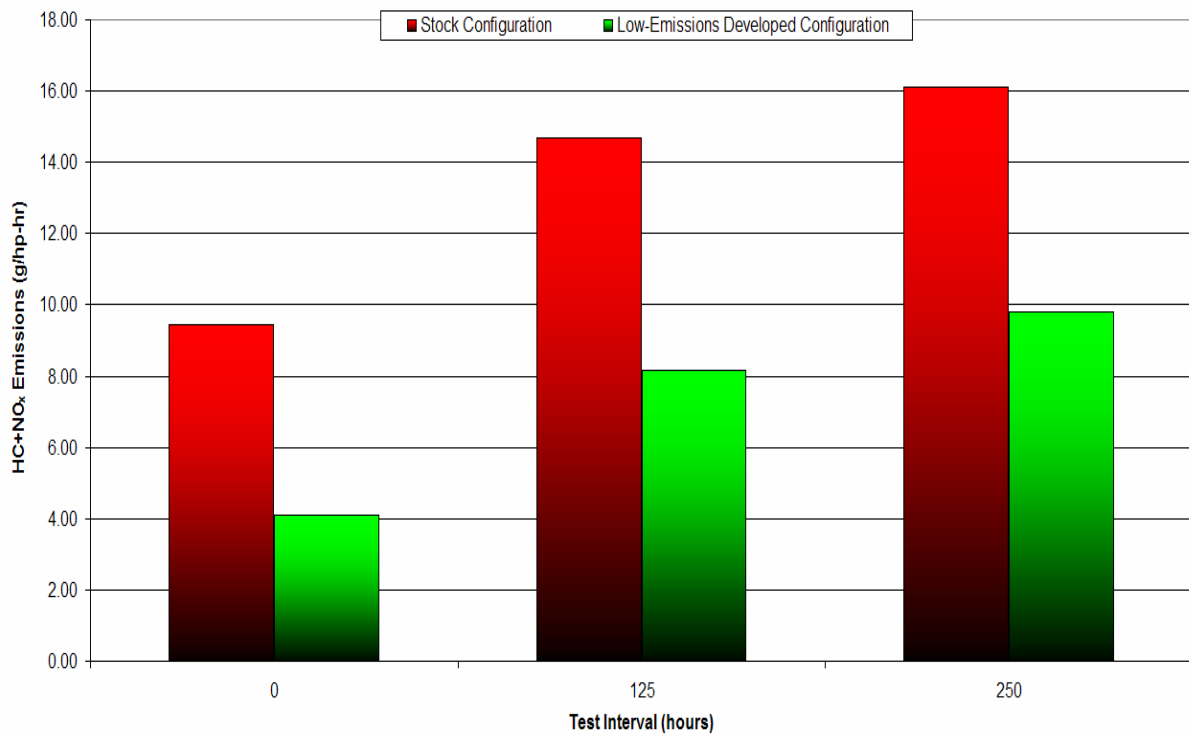


FIGURE 36. HC+NO_x EMISSIONS OF BRIGGS AND STRATTON ENGINE NO. 2 AT TEST INTERVALS

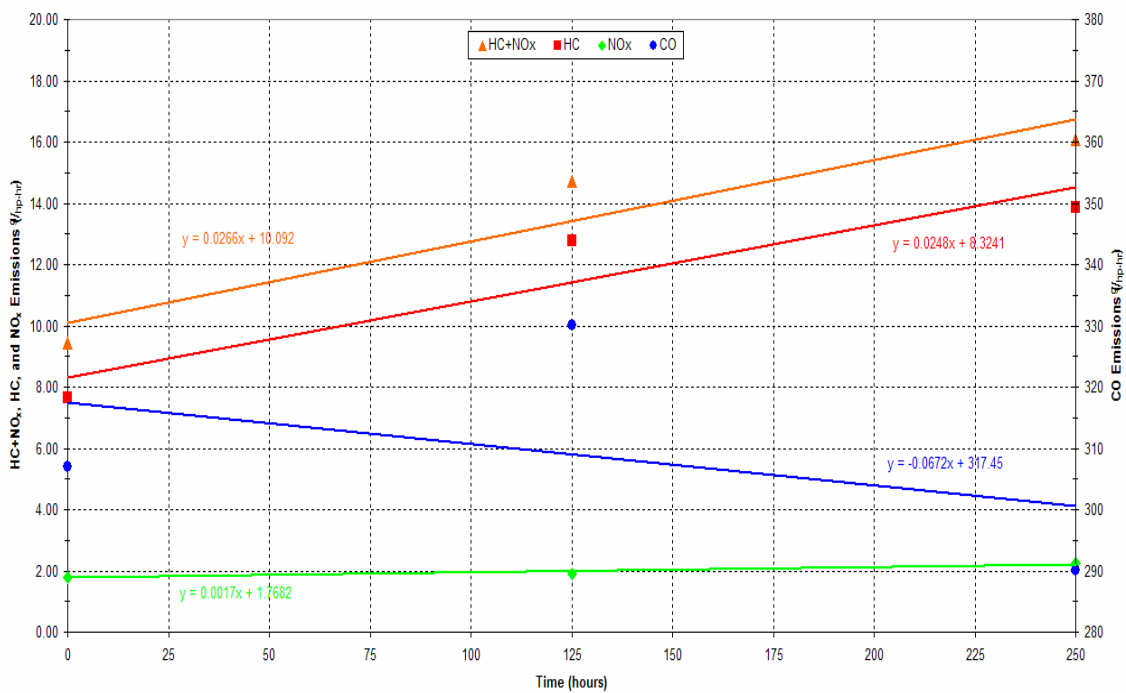


FIGURE 37. BRIGGS AND STRATTON NO. 2 EMISSIONS FOR STOCK CONFIGURATION

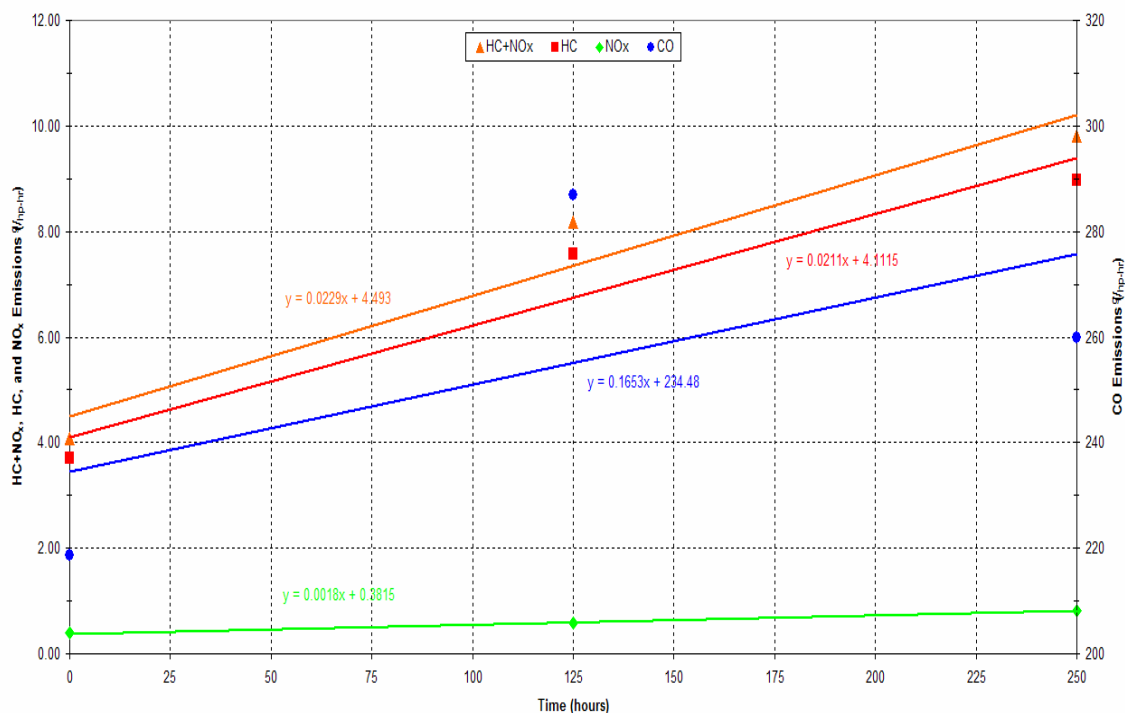


FIGURE 38. BRIGGS AND STRATTON NO. 2 EMISSIONS FOR DEVELOPED CONFIGURATION

TABLE 12. CALCULATED DETERIORATION FACTORS FOR BRIGGS AND STRATTON ENGINE NO. 2 THROUGH 250 HOURS

Time (hrs.)	Configuration	0-Hour Test No.	Interval Test No.	Deterioration Factors			
				HC+NO _x	HC	NO _x	CO
125	Developed	B+S #2-L-#3 & #4	B+S #2-125-L-#1 & #2	1.80	1.83	1.55	1.17
250	Developed	B+S #2-L-#3 & #4	B+S #2-250-L-#1 & #2	2.50	2.54	2.12	1.26

C. Tecumseh OVRM120 Engine

Tecumseh OVRM120 engine testing and development followed development of the first Briggs and Stratton engine. Upon review of the initial baseline results, Tecumseh and SwRI felt that the engine was not operating as it should. The engine was running slightly leaner than expected, resulting in higher NO_x emissions and elevated combustion temperatures. Checks were performed to verify proper fuel delivery, carburetor setup, and full throttle operation. Diagnostics were also performed to verify intake and exhaust valve lash, as well as to check for leakage past the piston rings. All checks verified correct setup and normal operation. To determine whether the problem was due to a faulty carburetor, a replacement carburetor was installed and tested. The engine ran leaner with the replacement carburetor, and it was concluded that a problem existed in the engine. It was decided to replace the Tecumseh engine with an identical engine ARB had previously used for evaporative emissions testing.

The replacement engine was baseline emissions tested and then developed in its low-emission configuration. Table 13 presents engine emission results. Individual test data sheets are presented in Appendix C. The developed Tecumseh engine utilized catalyst C integrated inside a muffler, with a passive SAI system. The engine was not enleaned as part of the development process. On average, the final zero-hour developed configuration reduced HC+NO_x emissions by 63 percent, HC emissions by 58 percent, NO_x emissions by 84 percent, and CO emissions by 53 percent. The final, average zero-hour emissions for the developed configuration were 2.54 g/hp-hr HC, 0.26 g/hp-hr NO_x, and 169 g/hp-hr CO. Zero-hour emission results for the baseline, baseline with catalyst C, and fully developed configurations (catalyst C and SAI) are shown in Figure 39.

TABLE 13. REPLACEMENT TECUMSEH OVRM120 ENGINE EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Baseline Emissions								
TEC2 BSLN #1	3.26	None	Stock (174)	5.45	4.74	1.58	7.03	337
TEC2 BSLN #2	3.33	None	Stock (174)	6.05	NA	1.65	7.70	342
TEC2 BSLN #3	3.00	None	Stock (174)	6.48	NA	1.54	8.02	405
BSLN Ave.	3.20			5.99	4.74	1.59	7.58	361
Development Emissions (0-Hour)								
TEC2-C-BSLN1m	3.58	Cat. C	Stock (174)	2.77	2.22	0.21	2.98	184
TEC2-C-BSLN2m	3.59	Cat. C	Stock (174)	2.31	NA	0.30	2.61	153
0 Cat. C Ave.	3.59			2.54	2.22	0.26	2.80	169
125-hour Emissions								
TEC2-125-STK-#1*	3.15	None	Stock (174)	8.07	7.08	1.33	9.40	375
TEC2-125-STK-#2	2.96	None	Stock (174)	9.27	8.20	1.49	10.76	411
TEC2-125-#1*	3.36	Cat. C	Stock (174)	4.47	3.69	0.27	4.74	256
TEC2-125-#2	3.21	Cat. C	Stock (174)	4.80	NA	0.47	5.27	247
TEC2-125-#3	3.18	Cat. C	Stock (174)	4.84	4.03	0.41	5.25	256
125 Cat. C Ave.	3.20			4.82	4.03	0.44	5.26	252
250-hour Emissions								
TEC2-250-STK-#1*	3.01	None	Stock (174)	8.43	7.34	1.49	9.93	397
TEC2-250-STK-#2	2.89	None	Stock (174)	9.58	8.38	1.70	11.28	457
TEC2-250-#1*	3.32	Cat. C	Stock (174)	3.32	2.64	0.33	3.65	230
TEC2-250-#2*	3.30	Cat. C	Stock (174)	3.55	2.76	0.31	3.86	250
250 Cat. C* Ave.	3.31			3.44	2.7	0.32	3.78	240
TEC2-250-#3	3.19	Cat. C	Stock (174)	3.79	2.91	0.36	4.15	286
TEC2-250-#4	3.15	Cat. C	Stock (174)	3.24	2.43	0.40	3.64	252
250 Cat. C Ave.	3.17			3.52	2.67	0.38	3.90	269
* Testing prior to maintenance								

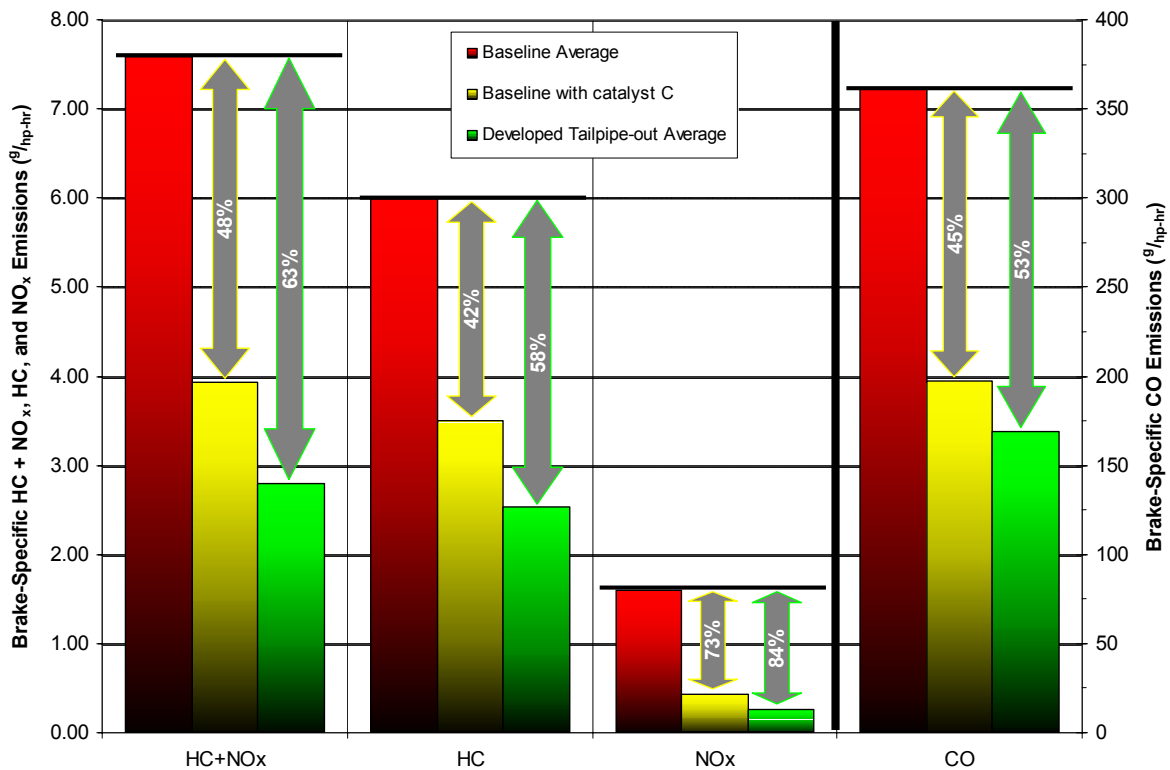


FIGURE 39. TECUMSEH OVRM120 ENGINE-- ZERO-HOUR EMISSIONS

The engine was emissions tested after completing the 125-hour service accumulation. No problems were experienced during the durability period. At 125 hours, the engine was tested in the stock-baseline and fully developed configurations, before and after scheduled maintenance. Maintenance included an oil change, air filter replacement, and spark plug replacement. Emissions after maintenance were higher than emissions prior to maintenance. The reason for this is unknown. On average at 125 hours, the developed configuration produced 5.08 g/hp-hr of HC+NO_x, 4.70 g/hp-hr of HC, 0.38 g/hp-hr of NO_x, and 253 g/hp-hr of CO. At 125 hours, the engine's stock-baseline HC+NO_x emissions increased by 42 percent compared to zero-hour data. Catalyst performance at 125 hours was on the order of 50 percent for HC+NO_x, 46 percent for HC, 73 percent for NO_x, and 36 percent for CO. After maintenance during the 125-hour emissions test, an oil leak was noticed near the head of the cylinder past the 'flange' gasket, as well as a leak around the o-ring at the bottom of the oil fill tube. Tecumseh mentioned that oil leakage past the 'flange' gasket has been observed on OVRM120s in the past. The leak past the oil fill tube may have been due to slightly higher crankcase pressures resulting from excess oil in the sump.

After completing the second and final durability interval, the engine was tested at 250 hours. No problems were experienced during the durability period. As at 125 hours, the engine was tested before and after scheduled maintenance in both the fully developed and stock-baseline configurations. As observed at 125 hours, tests after maintenance generated higher emissions than tests prior to maintenance, mostly from increased HC emissions. At 250 hours, the developed configuration produced an

average of 3.82 g/hp-hr of HC+NO_x, 3.47 g/hp-hr of HC, 0.35 g/hp-hr of NO_x, and 255 g/hp-hr of CO. Figure 40 shows HC+NO_x emission results at each test interval. Catalyst performance at 250 hours was 64 percent for HC+NO_x, 61 percent for HC, 78 percent for NO_x, and 40 percent for CO. Figures 41 and 42 show emissions results in stock and developed configurations, respectively, at each test interval. From these figures, it is noted that the durability data do not fall on a straight line, due to variability in engine operation. Using the least squares method, a set of deterioration factors was calculated for the Tecumseh engine at 125 and 250 hours. Deterioration factors are presented in Table 14. No additional problems were experienced during durability or testing with oil leakage past the flange gasket.

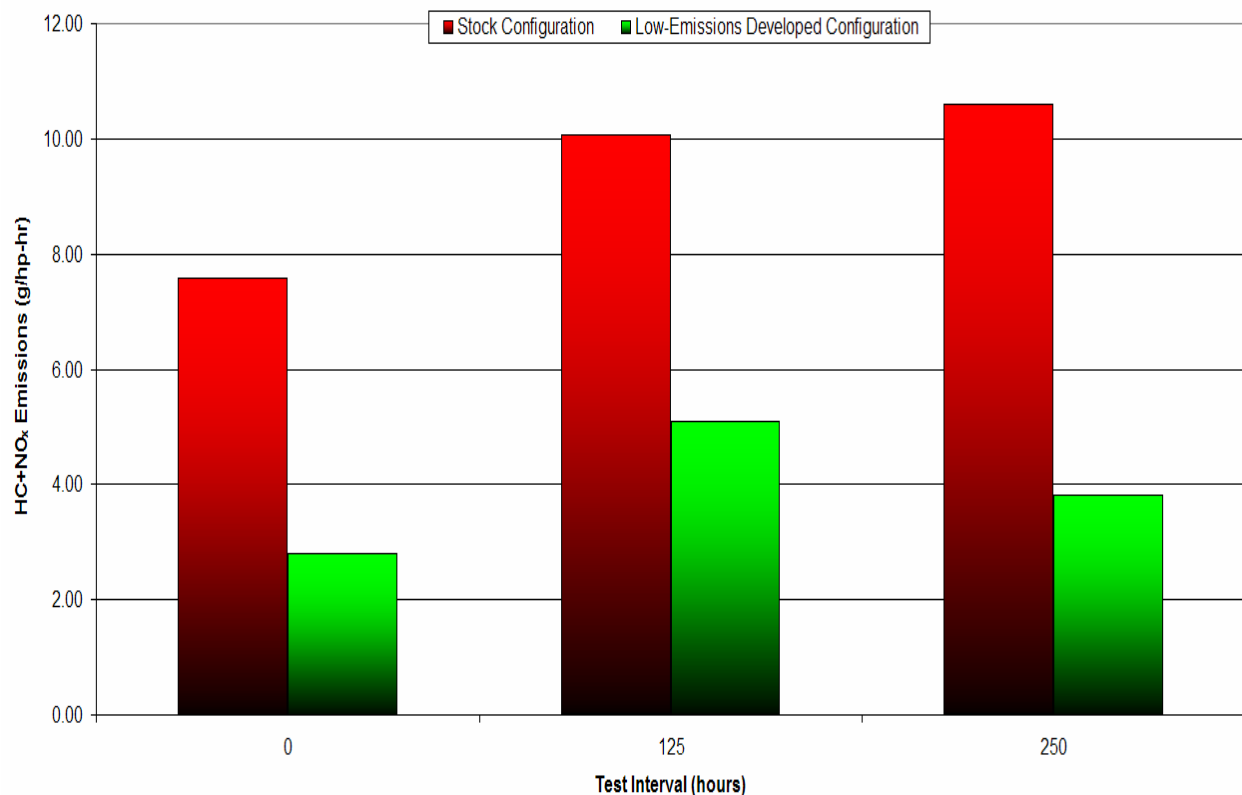


FIGURE 40. HC+NO_x EMISSIONS OF TECUMSEH OVRM120 ENGINE AT TEST INTERVALS

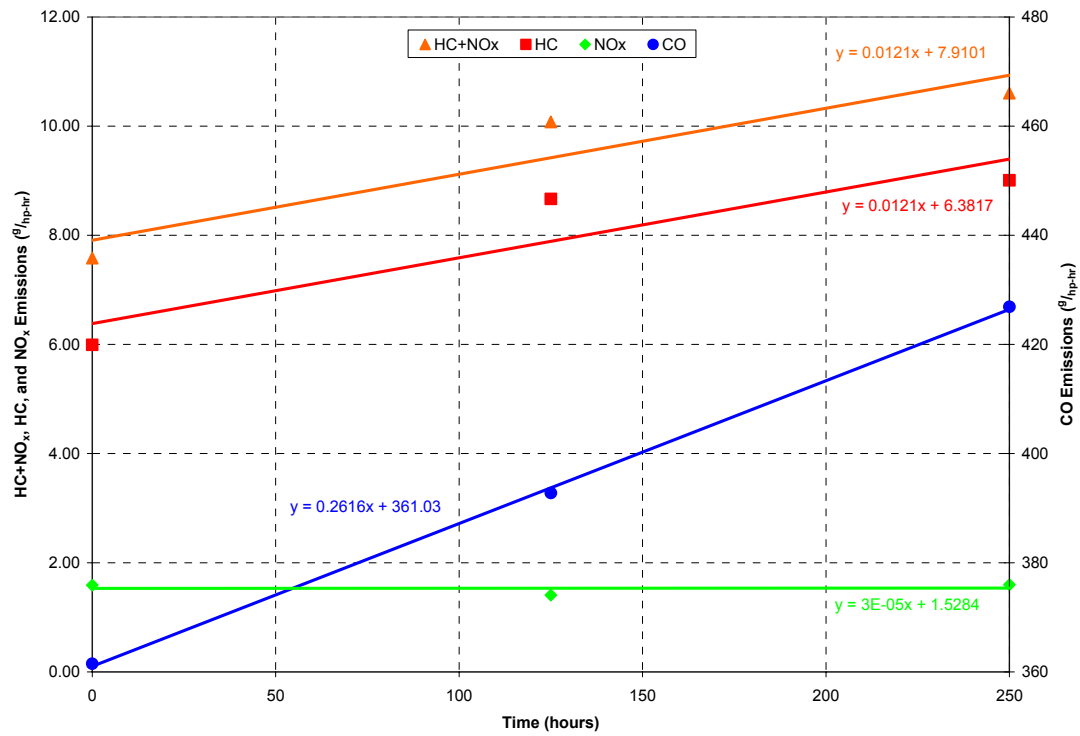


FIGURE 41. TECUMSEH OVRM120 EMISSIONS FOR STOCK CONFIGURATION

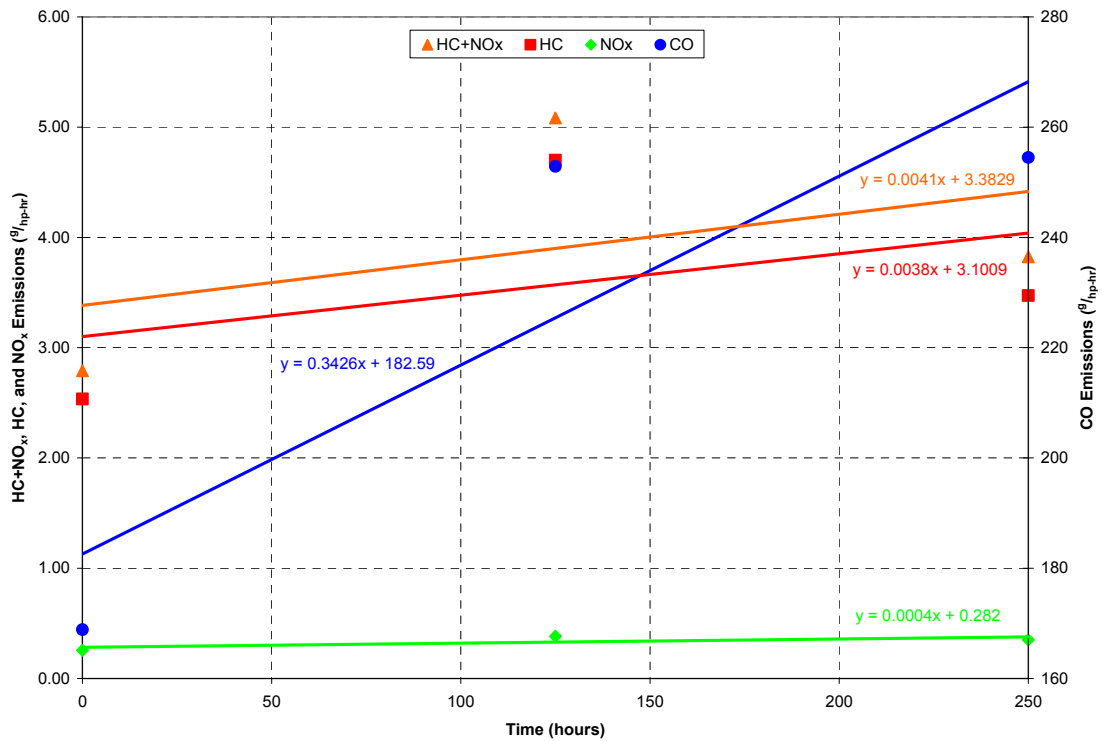


FIGURE 42. TECUMSEH OVRM120 EMISSIONS FOR DEVELOPED CONFIGURATION

**TABLE 14. CALCULATED DETERIORATION FACTORS FOR TECUMSEH
OVRM120 ENGINE THROUGH 250 HOURS**

Time (hrs.)	Configuration	0-Hour Test No.	Interval Test No.	Deterioration Factors			
				HC+NO _x	HC	NO _x	CO
125	Developed	TEC2-C-BSLN1m & 2m	TEC2-125-#1, #2, & #3	1.40	1.41	1.29	1.33
250	Developed	TEC2-C-BSLN1m & 2m	TEC2-250-#1, #2, #3, & # 4	1.58	1.59	1.48	1.59

D. Honda GCV160 Engine

It was originally planned to develop a 160 cc. displacement horizontal-shaft generator engine. CARB decided, however, to replace the horizontal-shaft Honda GX160 engine with a similar displacement GCV160 vertical-shaft engine that is used in walk-behind lawnmowers. The Honda GCV160 engine was baseline emissions tested in its stock configuration, then developed and durability tested. Results are summarized in Table 15. Individual test data sheets are presented in Appendix D.

TABLE 15. HONDA GCV160 ENGINE EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Baseline Emissions								
HON-160-BSLN#1	3.41	None	Stock-fixed	6.45	5.81	2.26	8.71	296
HON-160-BSLN#2	3.37	None	Stock-fixed	6.80	NA	2.17	8.97	303
HON-160-BSLN#3	3.54	None	Stock-fixed	6.20	NA	2.48	8.69	280
BSLN Ave.	3.44			6.48	5.81	2.30	8.79	293
Development Emissions (0-Hour)								
HON-160-J-BSLN#1	3.73	Cat. J	Stock-fixed	2.23	1.83	0.25	2.48	105
HON-160-J-BSLN#2	3.58	Cat. J	Stock-fixed	2.19	1.82	0.34	2.53	110
0 Cat. J Ave.	3.66			2.21	1.83	0.30	2.51	108
125-hour Emissions								
HON-160-STK-125-#1	3.18	None	Stock-fixed	5.16	4.78	5.46	10.62	157
HON-160-STK-125-#2	3.13	None	Stock-fixed	5.43	5.04	5.40	10.83	161
125 STK Ave.	3.16			5.30	4.91	5.43	10.73	159
HON-160-J-125-#1	3.40	Cat. J	Stock-fixed	1.52	1.29	0.47	1.99	66
HON-160-J-125-#2	3.35	Cat. J	Stock-fixed	1.52	1.27	0.58	2.10	62
125 Cat. J Ave.	3.38			1.52	1.28	0.53	2.05	64
250-hour Emissions								
HON-160-STK-250-#1	3.28	None	Stock-fixed	5.57	5.14	6.14	11.71	150
HON-160-STK-250-#1	3.40	None	Stock-fixed	4.95	4.57	6.01	10.96	141
250 STK Ave.	3.34			5.26	4.86	6.08	11.34	146
HON-160-J-250-#1	3.55	Cat. J	Stock-fixed	2.54	2.27	0.36	2.90	72
HON-160-J-250-#2	3.47	Cat. J	Stock-fixed	1.97	NA	0.44	2.41	78
250 Cat. J Ave.	3.51			2.26	2.27	0.40	2.66	75

The developed GCV160 engine utilized catalyst J integrated inside a modified GCV160 muffler, with a passive SAI system. The engine was not enleaned as part of the development process. On average, the zero-hour developed configuration reduced HC+NO_x emissions by 71 percent, HC emissions by 66 percent, NO_x emissions by 87

percent, and CO emissions by 63 percent. The final, average zero-hour emissions for the developed configuration were 2.21 g/hp-hr HC, 0.30 g/hp-hr NO_x, and 108 g/hp-hr CO. Figure 43 presents zero-hour emissions in the stock-baseline, baseline with catalyst J, and fully developed configurations (catalyst J with SAI).

The Honda GCV160 engine was emissions tested after completing the first 125-hour service accumulation. No problems were experienced during the durability period. At 125 hours, the engine was tested in the stock-baseline and fully developed configurations. Scheduled maintenance was performed every 50 hours during durability, including oil changes, air filter cleaning and replacement, and spark plug cleaning and regapping. On average at 125 hours, the developed configuration produced 2.04 g/hp-hr of HC+NO_x, 1.52 g/hp-hr of HC, 0.52 g/hp-hr of NO_x, and 64 g/hp-hr of CO. At 125 hours, catalyst percent conversions were 81 percent for HC+NO_x, 71 percent for HC, 90 percent for NO_x, and 60 percent for CO. The engine was running leaner at 125 hours than during baseline and development testing, resulting in increased NO_x emissions and reduced HC and CO emissions. It is believed that the increase in stock HC emissions at 125 hours was mostly from higher HC emissions at idle, due to leaner operation with potentially incomplete combustion. Also, the engine was harder to start, requiring the use of the choke, and idle operation was erratic.

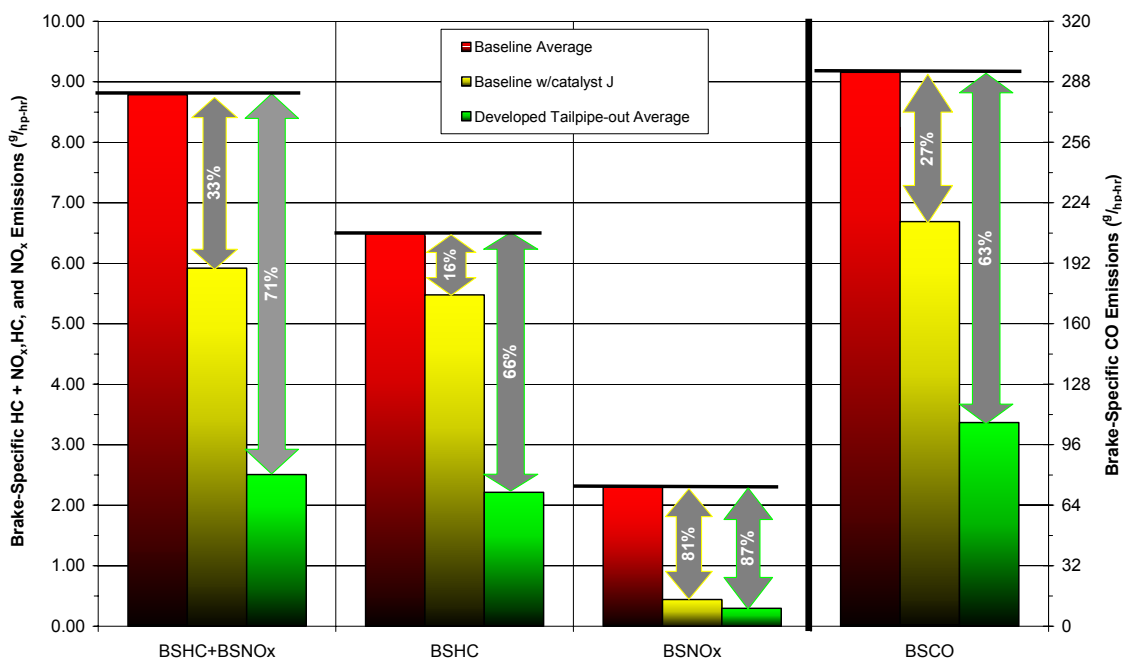


FIGURE 43. HONDA GCV160 ENGINE--ZERO-HOUR EMISSIONS

The engine was tested at 250 hours after completing the second durability interval. No problems were experienced during durability. Similar starting difficulty and erratic idle operation were observed as at 125 hours. Figure 44 shows HC+NO_x emissions at each test interval. On average at 250 hours, the developed configuration produced 2.66 g/hp-hr of HC+NO_x, 2.26 g/hp-hr of HC, 0.40 g/hp-hr of NO_x, and 75 g/hp-hr of CO. Catalyst performance at 250 hour was 77 percent for HC+NO_x, 57 percent for HC, 93 percent for NO_x, and 48 percent for CO. Figures 45 and 46 show

emissions results in stock and developed configurations, respectively, at each test interval. Using the least squares method, a set of deterioration factors was calculated for the Honda GCV160 engine at 125 and 250 hours, as shown in Table 16.

After completing 250-hour testing, carburetor maintenance was performed on the Honda GCV160 engine in an attempt to improve idle operation and startability. The carburetor was removed from the engine and cleaned according to Honda specified procedures. Upon removing the carburetor from the engine, a worn gasket was found between the carburetor and the intake port. The carburetor was thoroughly cleaned and reassembled, and a new gasket was fitted between the carburetor and the engine. A repeat set of tests was performed. Overall, composite emissions were only slightly affected by the carburetor maintenance. However, idle operation was less erratic and the engine did not run as lean at idle.

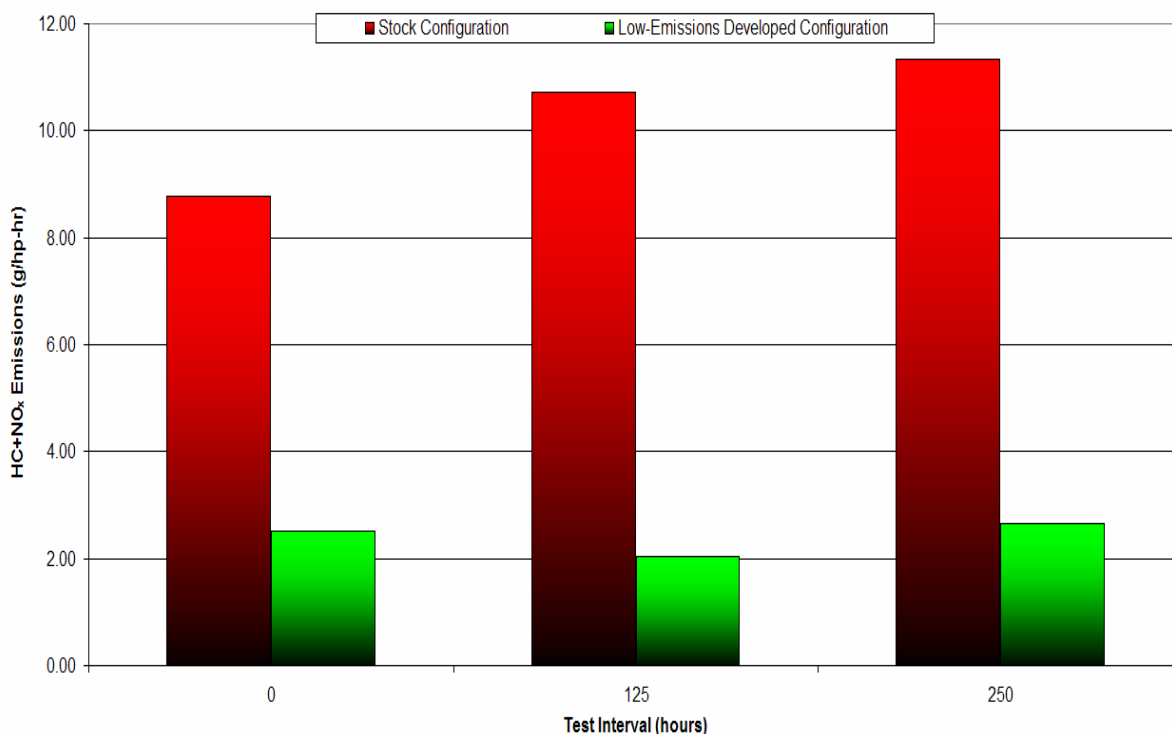


FIGURE 44. HC+NO_x EMISSIONS OF HONDA GCV160 ENGINE AT TEST INTERVALS

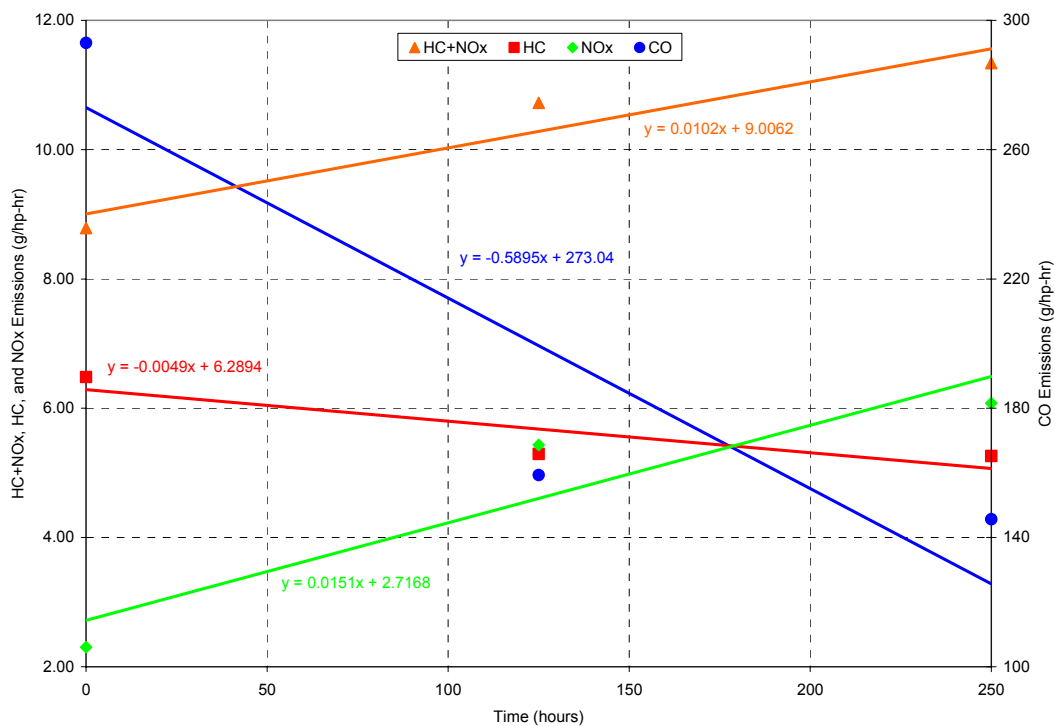


FIGURE 45. HONDA GCV160 EMISSIONS FOR STOCK CONFIGURATION

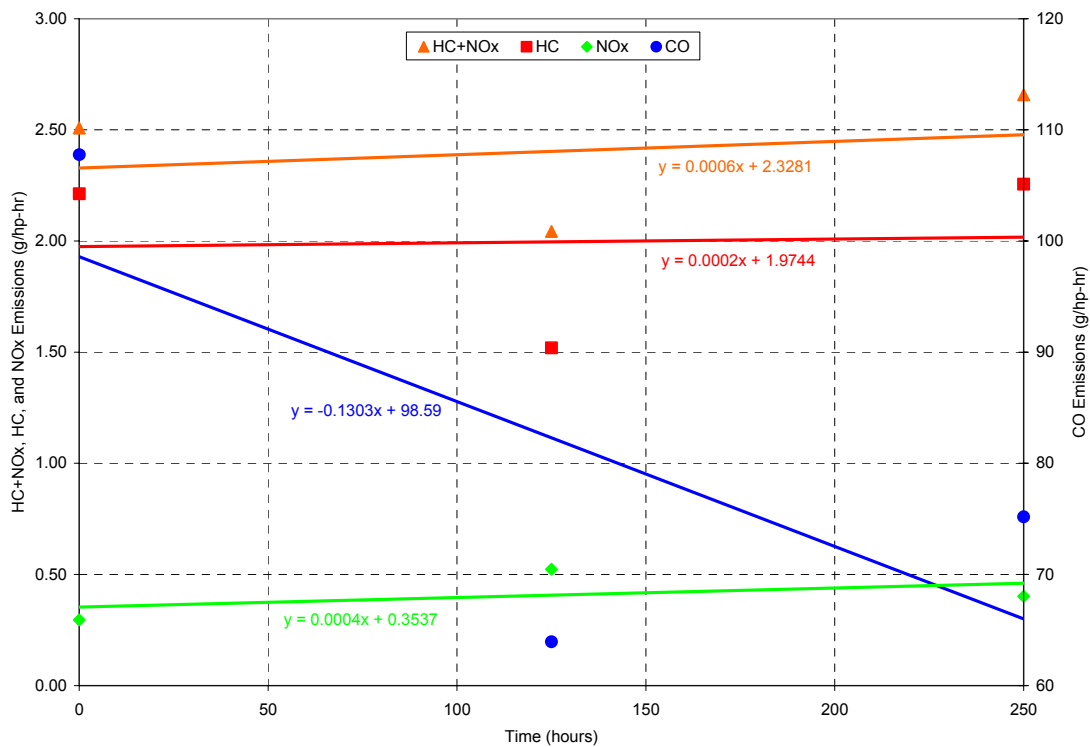


FIGURE 46. HONDA GCV160 EMISSIONS FOR DEVELOPED CONFIGURATION

**TABLE 16. CALCULATED DETERIORATION FACTORS FOR HONDA GCV160
ENGINE THROUGH 250 HOURS**

Time (hrs.)	Configuration	0-Hour Test No.	Interval Test No.	Deterioration Factors			
				HC+NO	HC	NO _x	CO
125	Developed	HON-160-J-BSLN#1 & #2	HON-160-J-125-#1 & #2	0.96	0.90	1.38	0.76
250	Developed	HON-160-J-BSLN#1 & #2	HON-160-J-250-#1 & #2	0.99	0.91	1.56	0.61

E. Kawasaki FH601V Engine

After completion of a two-hour break-in, the Kawasaki engine was found to be running noticeably leaner at high loads and richer at low loads, as compared to Kawasaki-supplied historical data. This was observed in exhaust gas oxygen sensor readings as well as engine-out emission data. It was suspected that there was a problem with the fuel system (filter and pump) or the carburetor, resulting in inadequate fueling at wide-open throttle and excess fueling at idle. A replacement carburetor from Kawasaki was installed. It exhibited similar performance, except with more reasonable fuel control at lower loads. From this data, it was suspected that there was an engine fuel delivery malfunction. A replacement engine was procured for testing.

The replacement engine was broken-in for two hours and then baseline tested. A set of four tests was run on this engine in the stock configuration. Consecutive tests were run on one day (*KAW2-BSLN#1* and *KAW2-BSLN#2*), and a second set of tests (*KAW2-BSLN#3* and *KAW2-BSLN#4*) were run the following day. Test No. 2 was considered invalid because of an emission measurement error during the idle mode, and was not used in the calculation of the baseline average. Emission results are summarized in Table 17. Individual test data sheets are presented in Appendix E.

Baseline results indicated variability in engine operation and emissions. To understand why this was observed, experiments were run at wide-open throttle with varied intake air temperatures. These experiments showed that fuel control and emissions for this engine are very sensitive to changes in intake air conditions (temperature and humidity). Test procedures were subsequently adjusted to more consistently maintain intake air temperature, however, intake air humidity could not be readily controlled.

TABLE 17. KAWASAKI FH601V ENGINE EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Baseline Emissions								
KAW2-BSLN#1	15.38	None	Stock (136/140)	6.63	5.49	1.27	7.90	418
KAW2-BSLN#3	16.12	None	Stock (136/140)	5.21	NA	2.08	7.29	386
KAW2-BSLN#4	15.60	None	Stock (136/140)	4.69	3.97	2.46	7.15	338
BSLN Ave.	15.70			5.51	4.73	1.94	7.45	380
Development Emissions								
KAW2-EO3-#1	15.23	None	Tier 3 (116/120)	3.55	NA	3.89	7.43	226
KAW2-E-DEV-FNL#1	15.56	Cat. E	Tier 3 (116/120)	1.45	1.06	0.07	1.52	111
KAW2-E-DEV-FNL#2	15.35	Cat. E	Tier 3 (116/120)	1.32	NA	0.05	1.37	101
0 Cat. E Ave.	15.46			1.39	1.06	0.06	1.45	106
125-hour Emissions								
KAW2-125-STK-#1	15.22	None	Stock (136/140)	5.70	5.25	0.86	6.56	410
KAW2-125-STK-#2	15.16	None	Stock (136/140)	6.08	5.24	0.76	6.84	435
125 STK Ave.	15.19			5.89	5.25	0.81	6.70	423
KAW2-125-EO3-#1	15.16	None	Tier 3 (116/120)	3.77	NA	4.16	7.93	199
KAW2-125-E-#1	15.39	Cat. E	Tier 3 (116/120)	1.67	1.23	0.10	1.77	128
KAW2-125-E-#2	15.34	Cat. E	Tier 3 (116/120)	1.52	1.09	0.07	1.59	119
125 Cat. E Ave.	13.37			1.60	1.16	0.09	1.68	124
250-hour Emissions								
KAW2-250-STK-#1	15.00	None	Stock (136/140)	7.54	6.47	0.85	8.39	435
KAW2-250-STK-#2	14.96	None	Stock (136/140)	7.70	NA	0.83	8.53	431
250 STK Ave.	14.98			7.62	6.47	0.84	8.46	433
KAW2-250-EO3-#1	14.93	None	Tier 3 (116/120)	4.10	NA	4.55	8.65	187
KAW2-250-EO3-#2	14.91	None	Tier 3 (116/120)	4.28	3.84	4.57	8.85	190
250 Tier 3 Ave.	14.92			4.19	3.84	4.56	8.75	189
KAW2-250-E-#1	14.97	Cat. E	Tier 3 (116/120)	1.83	1.38	0.11	1.94	126
KAW2-250-E-#2	14.79	Cat. E	Tier 3 (116/120)	1.77	1.32	0.10	1.87	126
KAW2-250-E-#3	14.94	Cat. E	Tier 3 (116/120)	1.78	NA	0.11	1.89	120
250 Cat. E Ave.	14.90			1.79	1.35	0.11	1.90	124
500-hour Emissions								
KAW2-500-STK-#1	15.52	None	Stock (136/140)	5.81	5.18	1.81	7.62	281
KAW2-500-STK-#2	15.49	None	Stock (136/140)	5.46	4.86	1.69	7.15	271
KAW2-500-STK-#3	15.25	None	Stock (136/140)	6.86	NA	0.88	7.74	388
KAW2-500-STK-#4	15.22	None	Stock (136/140)	7.18	NA	0.96	8.14	385
500 STK Ave.	15.37			6.33	5.02	1.34	7.66	331
KAW2-500-EO3-#1	15.07	None	Tier 3 (116/120)	4.27	3.83	4.86	9.13	179
KAW2-500-EO3-#2	15.31	None	Tier 3 (116/120)	4.33	3.87	4.47	8.80	179
500 Tier 3 Ave.	15.19			4.30	3.85	4.67	8.97	179
KAW2-500-E-#1	15.23	Cat. E	Tier 3 (116/120)	2.34	1.83	0.12	2.46	139
KAW2-500-E-#2	15.42	Cat. E	Tier 3 (116/120)	2.17	1.68	0.09	2.26	134
500 Cat. E Ave.	15.33			2.26	1.76	0.11	2.36	137

The developed configuration included catalyst E integrated inside a Kawasaki muffler, passive secondary air induction (SAI), and enleanment using fixed jets manufactured by Kawasaki for "Tier 3" lean settings. On average, the zero-hour developed configuration produced 1.45 g/hp-hr HC+NO_x, 1.39 g/hp-hr HC, 0.06 g/hp-hr NO_x, and 106 g/hp-hr CO. Overall, the developed configuration reduced HC+NO_x

emissions by 81 percent, HC by 75 percent, NO_x by 97 percent, and CO by 72 percent, as compared to average baseline results. Figure 47 summarizes emissions in baseline, baseline with catalyst E, developed engine-out, and developed configurations.

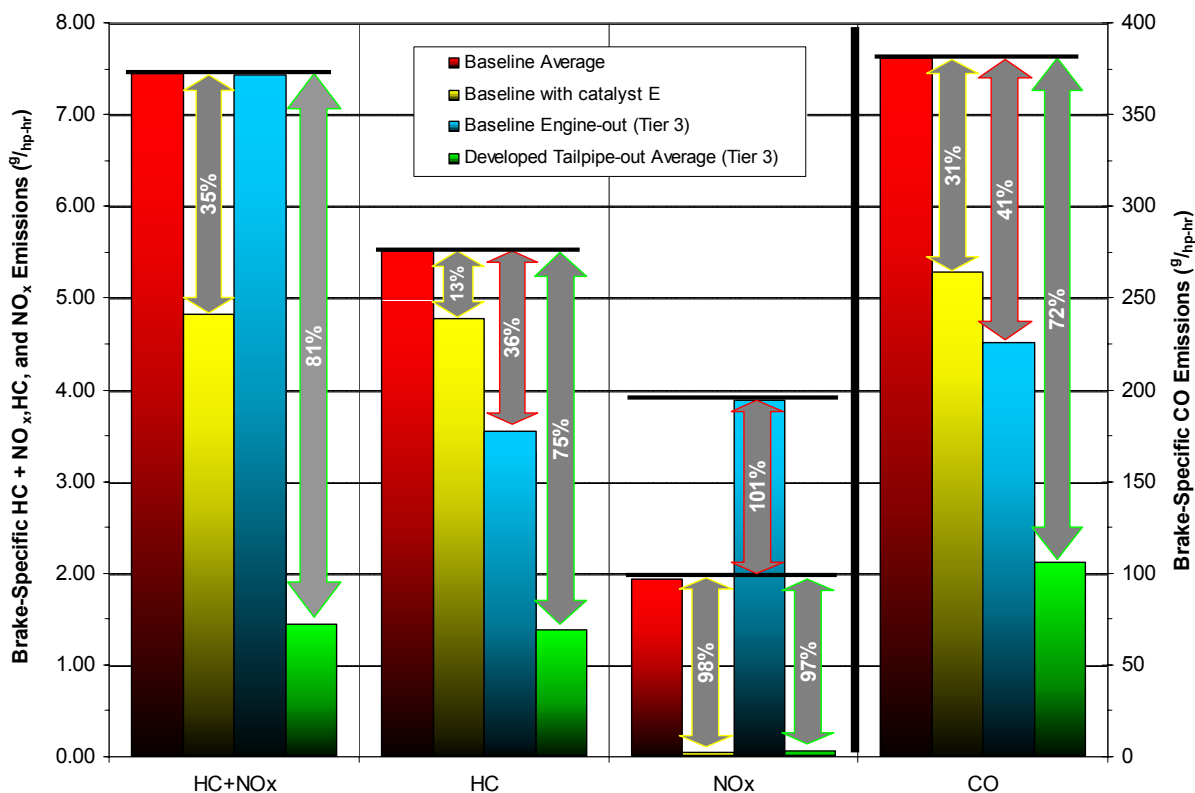


FIGURE 47. KAWASAKI FH601V ENGINE--ZERO-HOUR EMISSIONS

The engine was emission tested after 125 hours of service accumulation. No problems were experienced during durability. Scheduled maintenance was performed, including oil changes, air filter cleanings, and spark plug checks. At 125 hours the engine was running leaner at idle compared to baseline testing. Following aging, the engine was tested at 125 hours in the fully developed configuration, engine-out configuration ('Tier 3' jets with SAI system), and stock-baseline configuration. On average at 125 hours, the developed configuration produced 1.69 g/hp-hr of HC+NO_x, 1.60 g/hp-hr of HC, 0.09 g/hp-hr of NO_x, and 123 g/hp-hr of CO. Catalyst efficiency at 125 hours was 79 percent for HC+NO_x, 58 percent for HC, 98 percent for NO_x, and 38 percent for CO.

After completing the second durability interval, the engine was tested at 250 hours. No problems were experienced during durability. Scheduled maintenance was performed, including oil changes, air filter cleanings, and spark plug checks. On average at 250 hours, the developed configuration produced 1.91 g/hp-hr of HC+NO_x, 1.80 g/hp-hr of HC, 0.11 g/hp-hr of NO_x, and 124 g/hp-hr of CO. Catalyst efficiency at 250 hours was 78 percent for HC+NO_x, 57 percent for HC, 98 percent for NO_x, and 34 percent for CO.

As observed with the Honda GCV160 engine, the Kawasaki appeared to be running slightly leaner at idle than during baseline testing and development. A fuel conditioner was run through the engine after 250-hour testing, however, no change in operation was observed. After the 250-hour emissions tests, the ceramic insulators of the original spark plugs appeared to be slightly burned. The spark plugs were replaced prior to beginning the aging through 500 hours.

After completing the final durability interval, the engine was tested at 500 hours. No problems were experienced during durability. Scheduled maintenance was performed, including oil changes, air filter cleanings, and spark plug checks. On average at 500 hours, the developed configuration produced 2.36 g/hp-hr of HC+NO_x, 2.26 g/hp-hr of HC, 0.10 g/hp-hr of NO_x, and 136 g/hp-hr of CO. Figure 48 shows HC+NO_x emissions at each interval. At 500 hours, the engine in its stock configuration, continued to show signs of variability in operation and emissions. Catalyst percent conversions at 500 hours were 74 percent for HC+NO_x, 48 percent for HC, 98 percent for NO_x, and 24 percent for CO. Figures 49 and 50 show emissions results in baseline and developed configurations, respectively, at each test interval. Using the least squares method, a set of deterioration factors was calculated for the Kawasaki FH601V engine at 125, 250, and 500 hours, as shown in Table 18.

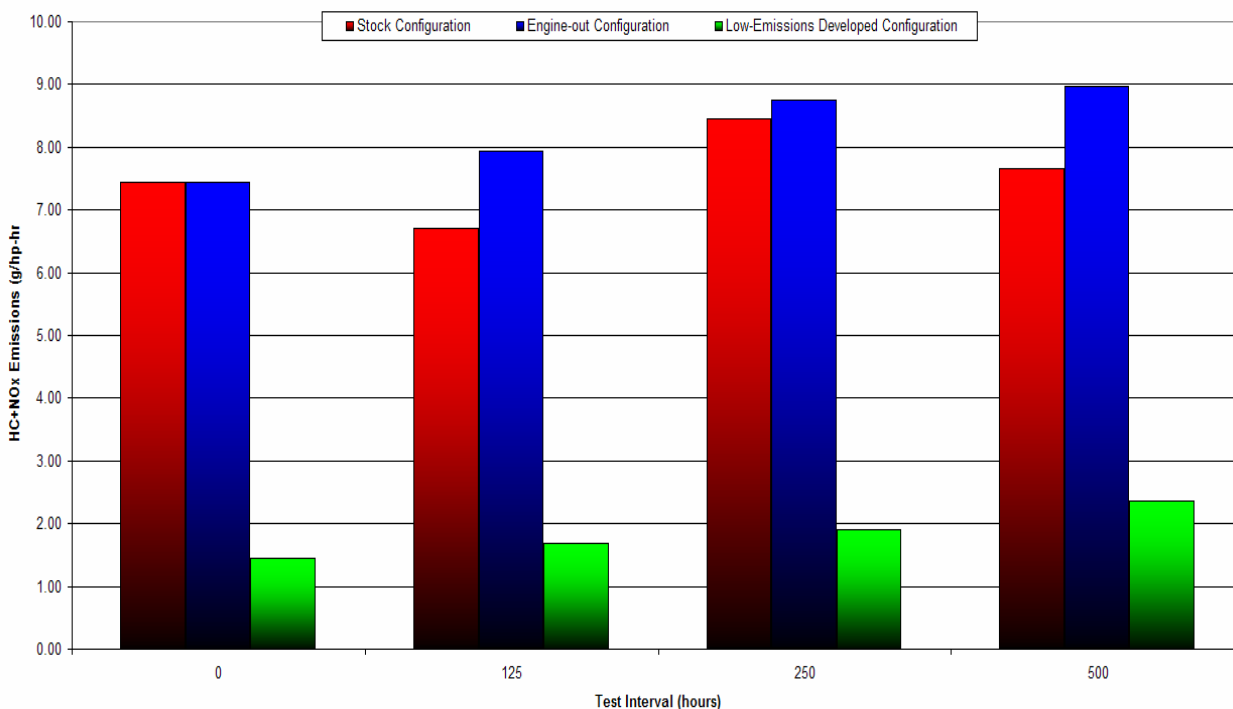


FIGURE 48. HC+NO_x EMISSIONS OF KAWASAKI FH601V ENGINE AT TEST INTERVALS

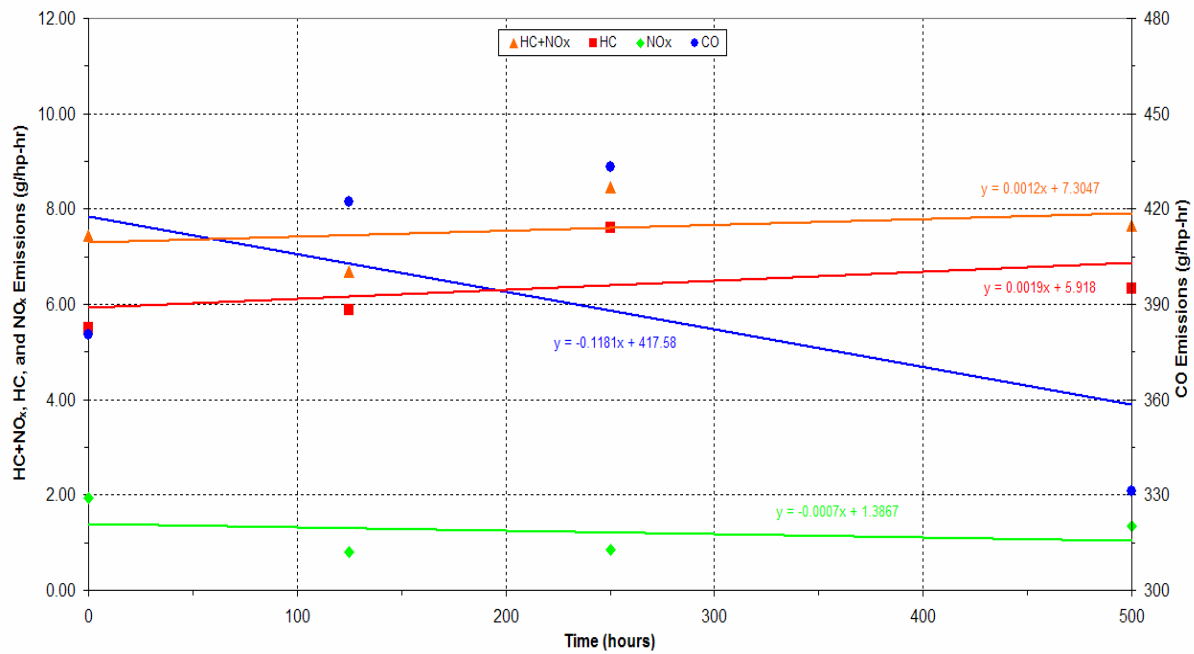


FIGURE 49. KAWASAKI FH601V EMISSIONS FOR STOCK CONFIGURATION

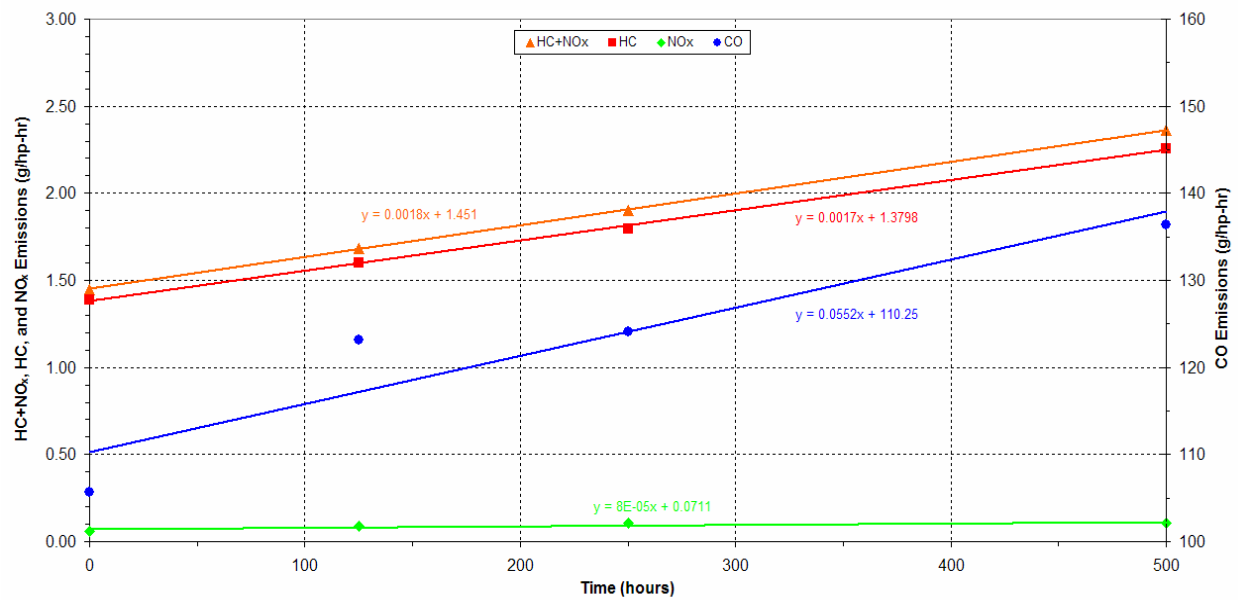


FIGURE 50. KAWASAKI FH601V EMISSIONS FOR DEVELOPED CONFIGURATION

**TABLE 18. CALCULATED DETERIORATION FACTORS FOR KAWASAKI
FH601V ENGINE THROUGH 500 HOURS**

Time (hrs.)	Configuration	0-Hour Test No.	Interval Test No.	Deterioration Factors			
				HC+NO _x	HC	NO _x	CO
125	Engine-Out	KAW2-EO3-#1	KAW2-125-EO3-#3	1.07	1.07	1.07	0.91
125	Developed	KAW2-E-DEV-FNL#1 & #2	KAW2-125-E-#1 & #2	1.16	1.15	1.35	1.11
250	Engine-Out	KAW2-EO3-#1	KAW2-250-EO3-#1 & #2	1.13	1.13	1.12	0.87
250	Developed	KAW2-E-DEV-FNL#1 & #2	KAW2-250-E-#1, #2, & #3	1.32	1.31	1.52	1.17
500	Engine-Out	KAW2-EO3-#1	KAW2-500-EO3-#1 & #2	1.23	1.24	1.22	0.77
500	Developed	KAW2-E-DEV-FNL#1 & #2	KAW2-500-E-#1 & #2	1.63	1.62	1.87	1.30

F. Honda GX340 Engine

Baseline testing and development of the Honda GX340 engine followed development of the second Briggs and Stratton engine. The developed engine configuration utilized catalyst I2 integrated inside a modified Honda GX340 muffler, stock carburetion, and no secondary air injection. Catalyst I2 is a 600 cpsi, metallic substrate 68 mm in diameter by 65 mm long, extracted from a 118 mm by 65 mm catalyst. Due to the design of the stock engine's exhaust system (cast-iron exhaust manifold with a close-coupled muffler), catalyst bed temperatures near 1620°F were observed during wide-open throttle operation at 3600 RPM. While these bed temperatures are higher than observed with other engines, the catalyst supplier indicated that the catalyst's technology has good high temperature durability and should continue to exhibit good performance. Secondary air induction was not utilized. Figure 51 summarizes 0-hour emissions in the baseline and developed configurations. On average, the zero-hour developed configuration produced 1.81 g/hp-hr HC+NO_x, 1.56 g/hp-hr HC, 0.24 g/hp-hr NO_x, and 121 g/hp-hr CO. The developed configuration reduced zero-hour HC+NO_x emissions by 72 percent, HC emissions by 60 percent, NO_x emissions by 91 percent, and CO emissions by 45 percent. Results are summarized in Table 19.

TABLE 19. HONDA GX340 ENGINE EMISSION RESULTS

Test No.	Mode 1 Power, hp	Catalyst	Carburetor Jetting	g/hp-hr				
				THC	NMHC	NO _x	THC+NO _x	CO
Baseline Emissions								
HON-340-BSLN#3r	9.69	None	Stock-fixed	3.89	3.42	2.65	6.54	215
HON-340-BSLN#4r	9.49	None	Stock-fixed	4.01	NA	2.56	6.57	222
BSLN Ave.	9.59			3.95	3.42	2.60	6.55	219
Development Emissions (0-Hour)								
HON-340-I2-BSLN-#2	9.37	Cat. I2	Stock-fixed	1.47	NA	0.25	1.72	120
HON-340-I2-BSLN-#3	9.74	Cat. I2	Stock-fixed	1.66	1.30	0.24	1.89	121
0 Cat I2 Ave.	9.56			1.57	1.30	0.25	1.81	121
125-hour Emissions								
HON-340-STK-125-#1	9.54	None	Stock-fixed	4.20	3.70	2.54	6.75	228
HON-340-STK-125-#2	9.12	None	Stock-fixed	4.43	NA	2.43	6.85	258
125 STK Ave.	9.33			4.32	3.70	2.49	6.8	243
HON-340-I2-125-#1	9.59	Cat. I2	Stock-fixed	2.31	1.81	0.10	2.41	208
HON-340-I2-125-#2	9.97	Cat. I2	Stock-fixed	2.08	NA	0.10	2.18	203
125 Cat. I2 Ave.	9.78			2.20	1.81	0.10	2.30	206
250-hour Emissions								
HON-340-STK-250-#1	9.46	None	Stock-fixed	5.63	5.06	2.16	7.80	253
HON-340-STK-250-#2	9.37	None	Stock-fixed	5.22	4.89	2.31	7.48	257
250 STK Ave.	9.42			5.43	4.98	2.24	7.64	255
HON-340-I2-250-#1	9.97	Cat. I2	Stock-fixed	1.59	1.19	0.22	1.81	140
HON-340-I2-250-#2	9.83	Cat. I2	Stock-fixed	1.68	NA	0.20	1.88	143
250 Cat. I2 Ave.	9.9			1.64	1.19	0.21	1.85	142
500-hour Emissions								
HON-340-STK-500-#1	9.26	None	Stock-fixed	5.75	5.10	2.27	8.02	234
HON-340-STK-500-#2	9.21	None	Stock-fixed	5.68	NA	2.19	7.87	236
500 STK Ave.	9.24			5.72	5.10	2.23	7.95	235

The engine was tested after completing the initial 125-hour durability period. Scheduled maintenance was performed, including oil changes, air filter cleanings, and spark plug checks. At 125 hours, the developed configuration produced an average of 2.29 g/hp-hr HC+NO_x, 2.19 g/hp-hr HC, 0.10 g/hp-hr NO_x, and 206 g/hp-hr CO. Catalyst percent conversions at 125 hours were 66 percent for HC+NO_x, 49 percent for HC, 96 percent for NO_x, and 15 percent for CO.

After 125-hour testing, the engine resumed durability and was emission tested at 250 hours. Scheduled maintenance was performed, including oil changes, air filter cleanings, and spark plug checks. At 250 hours, the developed configuration produced an average of 1.85 g/hp-hr HC+NO_x, 1.63 g/hp-hr HC, 0.21 g/hp-hr NO_x, and 141 g/hp-hr CO. Catalyst percent conversions at 250 hours were 76 percent for HC+NO_x, 70 percent for HC, 90 percent for NO_x, and 45 percent for CO. From the results at 250 hours, it was noticed that the engine was running leaner than observed at 0 and 125 hours, resulting in lower HC and CO emissions and higher NO_x emissions.

During the final durability period, the developed exhaust system malfunctioned causing the catalyst to come loose from its containment. This occurred shortly after returning to durability, approximately 15 hours after 250-hour testing was performed. It

was determined that the catalyst seals vibrated loose causing the hot exhaust gases to deteriorate the intumescent matting (Interam) allowing the catalyst to vibrate loose. Since the catalyst was damaged beyond repair, the engine continued aging with a stock exhaust system and was then tested in the stock configuration at 500 hours. From the stock emissions measured at 500 hours, predicted emissions at 500 hours with catalyst were calculated based on catalyst efficiencies at 0, 125, and 250 hours. Figure 52 shows HC+NO_x emissions at each test interval. At 500 hours, the stock configuration produced an average of 7.94 g/hp-hr HC+NO_x, 5.71 g/hp-hr HC, 2.23 g/hp-hr NO_x, and 235 g/hp-hr CO. Predicted development emissions at 500 hours are 2.04 g/hp-hr HC+NO_x, 1.90 g/hp-hr HC, 0.14 g/hp-hr NO_x, and 187 g/hp-hr CO. Figures 53 and 54 show emissions results in baseline and developed configurations, respectively, at each test interval. Using the least squares method, a set of deterioration factors was calculated for the Honda GX340 engine at 125, 250, and 500 hours, as shown in Table 20.

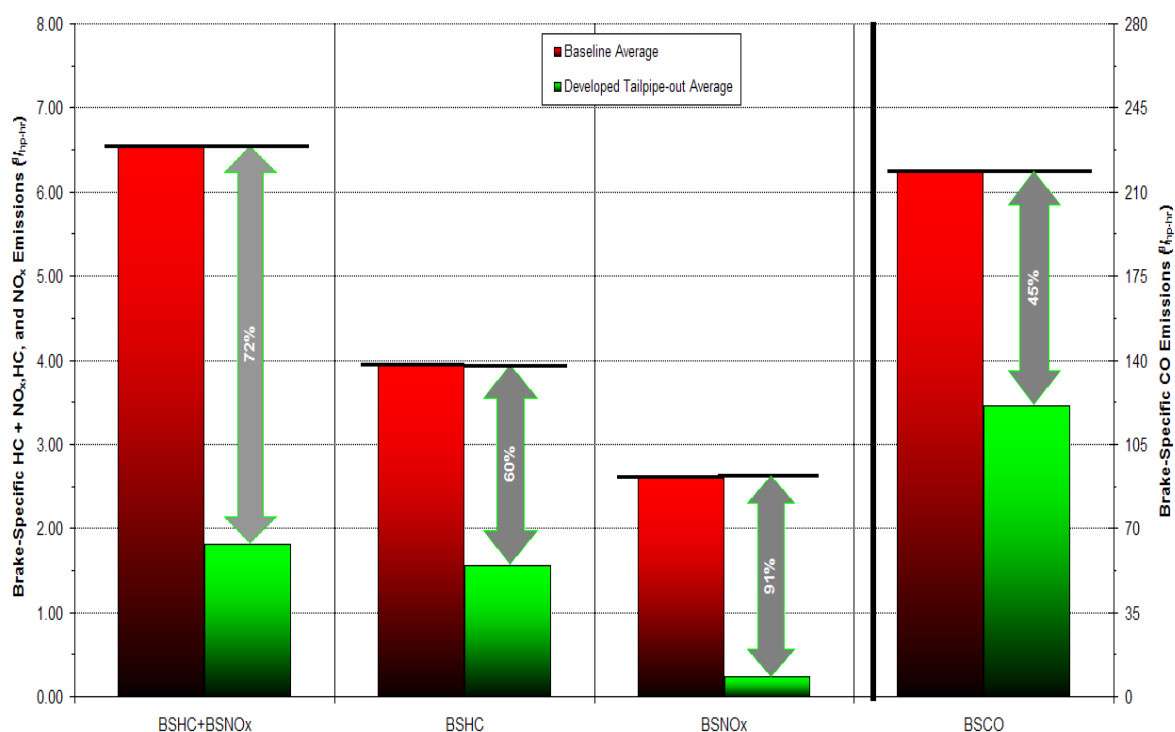


FIGURE 51. HONDA GX340 ENGINE--ZERO-HOUR EMISSIONS

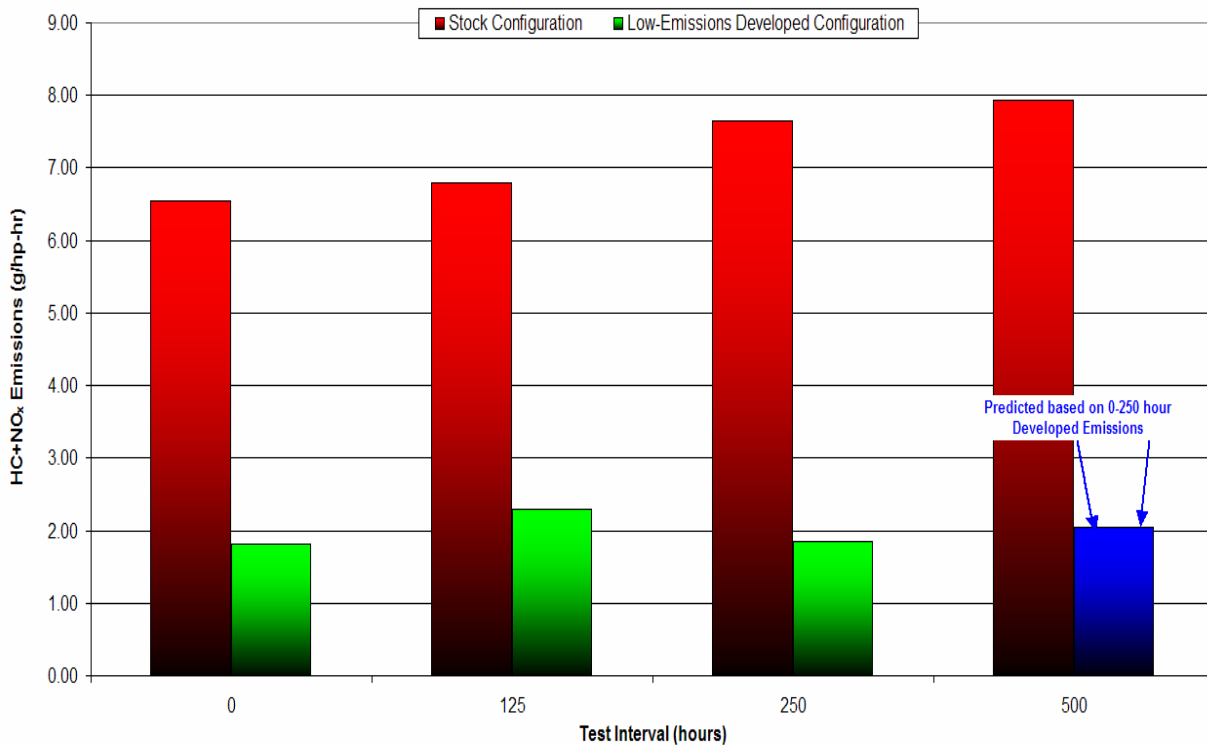


FIGURE 52. HC+NO_x EMISSIONS OF HONDA GX340 ENGINE AT TEST INTERVALS

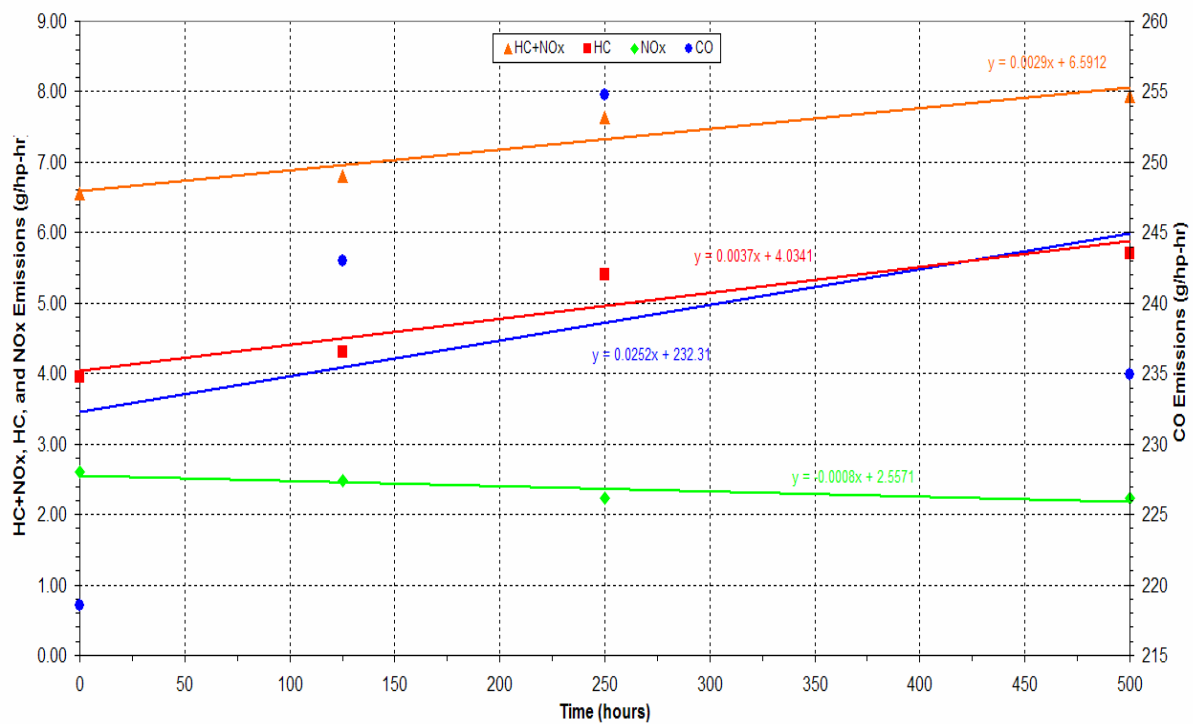


FIGURE 53. HONDA GX340 EMISSIONS FOR STOCK CONFIGURATION

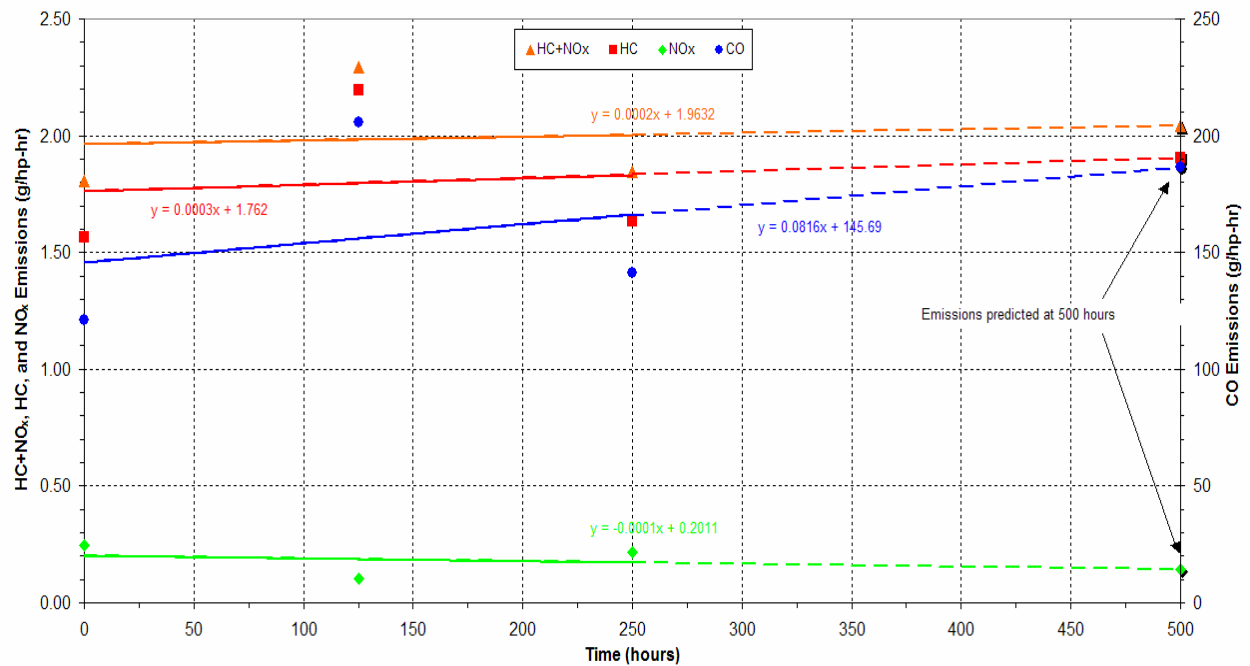


FIGURE 54. HONDA GX340 EMISSIONS FOR DEVELOPED CONFIGURATION

TABLE 20. CALCULATED DETERIORATION FACTORS FOR HONDA GX340 ENGINE THROUGH 500 HOURS

Time (hrs.)	Configuration	0-Hour Test No.	Interval Test No.	Deterioration Factors			
				HC+NO _x	HC	NO _x	CO
125	Developed	HON-340-I2-BSLN#2 & #3	HON-340-I2-125-#1 & #2	1.10	1.15	0.76	1.29
250	Developed	HON-340-I2-BSLN#2 & #3	HON-340-I2-250-#1 & #2	1.11	1.17	0.70	1.37
500	Developed	HON-340-I2-BSLN#2 & #3	Testing not performed	NA	NA	NA	NA

IV. SUMMARY AND CONCLUSIONS

Six small, off-road engines were developed in low-emission configurations and aged through their useful lives to demonstrate the effectiveness and durability of catalyst application. Four of the engines are used in walk-behind mower (WBM) applications, one is for a riding mower, and one is used in constant-speed/generator applications. The program goal was to reduce HC+NO_x emissions at the end of the engine's useful lives by at least 50 percent as compared to current CARB standards. Low-emission engines were developed using three-way catalytic converters, passive secondary-air induction (SAI) systems, and in some cases enleanment.

Variability in engine operation and emissions presented additional challenges. One of the developed engines exhibited extreme engine deterioration and was removed from the program. Two of the six engines tested were replaced at zero hours due to questions about their initial operation. Engine fueling characteristics and resulting emissions were observed to shift from one durability interval to the next. Good results were obtained in spite of these difficulties and show that even better emission results could be achieved with better engine design.

As shown in Figure 55, results demonstrated that emissions from these engines can be significantly reduced. The project goal of a 50 percent minimum HC+NO_x reduction at useful life was successfully demonstrated on three of the six engines. The Honda GX340 engine would likely also have met this goal if the catalyst seals had not failed (predicted results shown).

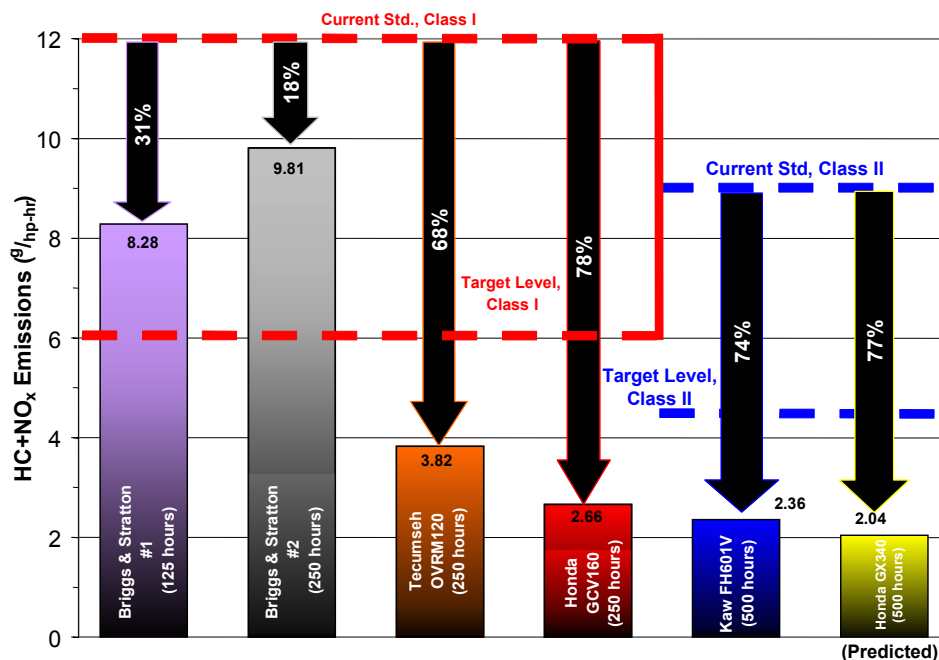


FIGURE 55. DEVELOPED ENGINE EMISSIONS

Emissions were reduced from the first Briggs and Stratton engine using a three-way catalyst, a passive SAI system, and enleanment. The engine was removed from the program after 125 hours due to engine deterioration. Overall emission reductions at 125 hours were poor, primarily due to a large increase in engine-out emissions. In spite of the engine deterioration, the catalyst held up well, reducing engine-out HC+NO_x emissions at 125 hours by 58 percent, and CO emissions by 59 percent. While the engine may have been deteriorated by the somewhat leaner calibration employed, there were already indications of engine problems at zero hours, prior to beginning durability.

The second Briggs and Stratton engine successfully completed 250 hours of durability. The developed, low emissions configuration included a three-way catalyst and a passive SAI system. The stock engine air/fuel calibration was not altered due to experience with the first Briggs engine. At 250 hours, the developed engine emitted 4 percent higher HC+NO_x emissions, and 14 percent higher HC emissions, and reduced NO_x and CO emissions by 54 and 15 percent, respectively, as compared to 0-hour baseline emissions. Catalyst performance at 250 hours was 39 percent for HC+NO_x, 35 percent for HC, 63 percent for NO_x, and 10 percent for CO.

The Tecumseh OVRM120 engine successfully completed 250 hours of durability. The developed, low emissions configuration included a three-way catalyst and a passive SAI system. The stock engine air/fuel calibration was not altered. At 250 hours, emissions were reduced by 50 percent for HC+NO_x, 42 percent for HC, 78 percent for NO_x, and 30 percent for CO, as compared to 0-hour baseline emissions. Catalyst performance at 250 hours was 64 percent for HC+NO_x, 61 percent for HC, 78 percent for NO_x, and 40 percent for CO.

The Honda GCV160 engine successfully completed 250 hours of durability. The developed, low emissions configuration included a three-way catalyst and a passive SAI system. As was the case with the second Briggs and Tecumseh engines, the stock engine calibration was not changed. At 250 hours, HC+NO_x emissions were reduced by 70 percent, HC by 65 percent, NO_x by 83 percent, and CO by 74 percent, as compared to 0-hour baseline emissions. Catalyst performance held up well with 250-hour conversions of 77 percent for HC+NO_x, 57 percent for HC, 93 percent for NO_x, and 48 percent for CO.

The Kawasaki FH601V engine successfully completed 500 hours of durability. The developed configuration included a three-way catalyst, passive SAI system, and enleanment. At 500 hours, HC+NO_x emissions were reduced by 68 percent, HC by 59 percent, NO_x by 95 percent, and CO by 64 percent, as compared to 0-hour baseline emissions. Catalyst percent conversions at 500 hours were 69 percent for HC+NO_x, 64 percent for HC, 92 percent for NO_x, and 59 percent for CO.

The developed Honda GX340 engine successfully completed 250 hours. The catalyst mounting failed at approximately 265 hours, so the engine continued aging to 500 hours in the stock configuration. The developed, low emissions configuration included a three-way catalyst integrated in a modified muffler. As was the case with the

second Briggs, Tecumseh and Honda GCV160 engines, the stock engine calibration was not changed. Due to the loss of the end seals for the modified metallic catalyst, the part vibrated loose in the muffler and was damaged beyond repair. At 250 hours, HC+NO_x emissions were reduced by 72 percent, HC by 59 percent, NO_x by 92 percent, and CO by 35 percent, as compared to 0-hour baseline emissions. Catalyst performance held up well with 250-hour conversions of 76 percent for HC+NO_x, 70 percent for HC, 90 percent for NO_x, and 45 percent for CO.

Overall reductions in HC+NO_x emissions for all six engines, as compared to 0-hour baseline emissions, are shown in Figure 56. Catalyst performance on the six engines is shown in Figure 57, which summarizes percent HC+NO_x conversions at each test interval.

Engines were instrumented for temperature measurement as shown in Figures 1-6 and 20-31. Detailed temperature data is included in the Appendices. Application of catalysts caused increases in muffler out and muffler surface temperature. The magnitude of the temperature change was a function of engine flowrate, reactant quantities (HC, CO, and NO_x), oxygen level, catalyst activity, and mechanical configuration. Engine muffler out temperatures at 0-hour, mode 1 conditions (stock baseline vs. developed configuration, with catalyst), changed as follows:

Briggs and Stratton #1	+89°F
Briggs and Stratton #2	+32°F
Honda GCV 160	-86°F
Kawasaki	+261°F
Honda GX340	+200°F

The largest increases were with the two highest horsepower engines, as expected. Note that these are prototype systems that have not been engineered for temperature control. There are a number of design approaches that can be applied to production engines to minimize these temperature increases.

It should be kept in mind that the developed catalyzed exhaust systems are prototype systems, developed for the purpose of a demonstration. They are by no means optimized for size or cost. Catalysts were conservatively chosen in order to meet program goals. Solutions employing smaller and less expensive catalysts can likely achieve similar performance with additional development.

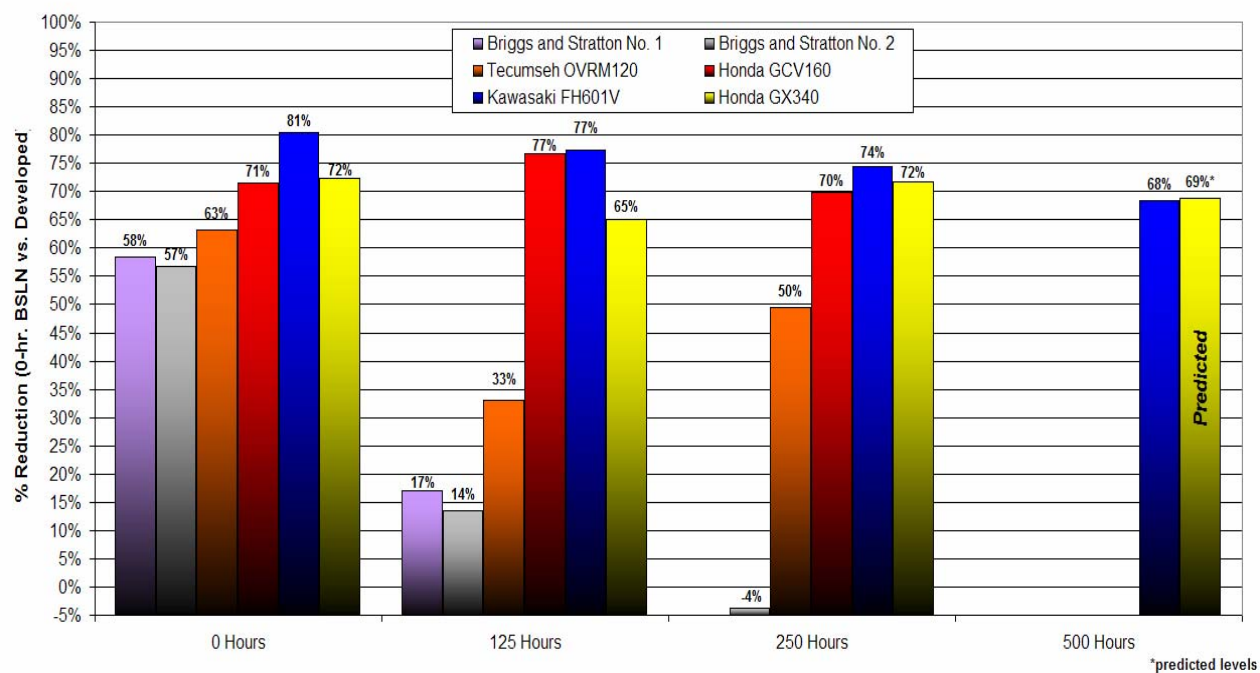


FIGURE 56. HC+NO_x EMISSION REDUCTIONS COMPARED TO 0-HOUR BASELINE RESULTS

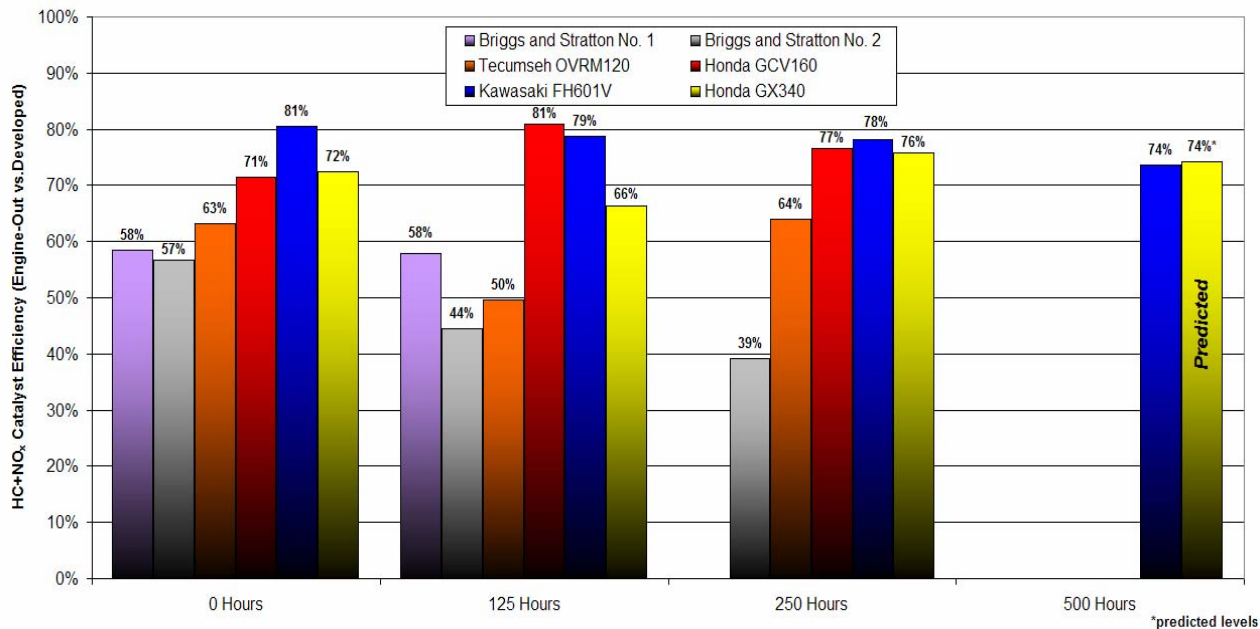


FIGURE 57. CATALYST HC+NO_x PERCENT CONVERSION VS. DURABILITY HOURS